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FIELD STUDY OF NITRIFICATION WITH THE SUBMERGED FILTER

Donald D. McHarness, et al

Stanford University

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Field Study of Nitrification with the Submerged Filter

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February 1973

FIELD STUDY OF NITRIFICATION WITH THE SUBMERGED FILTER

by

Donald D. McHarness
Perry L. McCarty

Grant #17010 EPM

Project Officer

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This study demonstrated the feasibility of a column packed with one-inch rock media to retain nitrifying organisms on the media surface. Kinetic rates of the nitrification reaction in secondary effluent, using two modes of oxygen aeration, were studied.

Successful and reliable nitrification of secondary activated sludge effluent was demonstrated in this field study using a pilot size packed media column. Ninety percent reduction of ammonia nitrogen and residual BOD and suspended solids of less than 10 mg/l was obtained with a detention time of one hour.

Two methods of oxygen introduction were evaluated. One system involved pre-oxygenation with pure oxygen at one atmosphere of pressure, and required recycle of treated effluent because of the limited oxygen solubility. This system achieved the greatest efficiency of BOD and solids removal, and was most reliable. This system did have a tendency to clog at high influent solids levels.

The other system, which employed direct bubbling of oxygen into the column, was only slightly less efficient and did not suffer from the clogging tendencies of the recycle system. (EPA)

17a. Descriptors

*Nitrification, *Biological Treatment, *Oxygen, Municipal Wastes, Biological Solids, *Waste water treatment, Alkalinity, Solid wastes, *Filters, Filtration, Aeration, Activated sludge, Suspended solids, Biochemical oxygen demand,

17b. Identifiers

*stage treatment, *packed column, field evaluation, alkalinity, temperature effect

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ABSTRACT

Successful and reliable nitrification of secondary activated sludge plant effluent was demonstrated in this field study using laboratory scale submerged rock filters and pure oxygen. The filter also operated as a highly effective polishing device reducing BOD and suspended solids by as much as 80 to 90 percent to levels of less than 10 mg/l.

About 90 percent reduction in ammonia nitrogen was obtained with a detention time of 60 minutes.

Two methods of oxygen introduction were evaluated. One system involved preoxygenation with pure oxygen at 1 atm of pressure, and required recycle of treated effluent because of limited oxygen solubility. This system achieved the greatest efficiency of BOD and suspended solids removal, and was most reliable, but greater efforts were required to prevent clogging.

The other system, which employed direct bubbling of oxygen into the filter, was estimated to be less costly because of a lower oxygen equipment requirement.

The respective estimated costs for treatment of 100 and 5 mgd are 2.8 and 4.8 cents per 1000 gal for a preoxygenation filter and 2.2 and 3.9 cents per 1000 gal for a bubble oxygenation filter.

This report was submitted in partial fulfillment of Research Grant No. 17010 EPM under the sponsorship of the Environmental Protection Agency by the Civil Engineering Department, Stanford University, Stanford, California 94305.

CONTENTS

Section		Page
I	Conclusions	1
II	Recommendations	3
III	Introduction	5
IV	Background	7
	Nitrification	7
	Results of laboratory studies on the submerged filter	12
V	Experimental Procedures	21
	The full-scale wastewater treatment plant preceding the pilot plant facilities	21
	Pilot plant apparatus	21
	Operational procedures	26
	Analytical techniques	28
VI	Results of Field Studies	33
	Characteristics of the influent wastewater	33
	Preoxygenation filter with recycle	33
	Bubble oxygenation filter	50
	Diurnal variation in operation	56
	Effluent nitrogen forms	59
VII	Summary and Discussion	61
	Operating results	61
	Comparison of the results from the field and laboratory studies	63
	Recycle ratio	65
	Advantages of the submerged filter	68
	Disadvantages of the submerged filter	69
	Estimated cost of treatment	69
VIII	Acknowledgements	73
IX	References	75
X	Publications	77
XI	List of Symbols	79
XII	Appendices	81

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FIGURES

		Page
1	Heterogeneous system composed of substrate in aqueous solution and microbial population in biological film.	10
2	Diffusion of major ions during nitrification in the submerged filter (2).	11
3	Flow rates for submerged filter with recycle.	15
4	Rate of ammonia-nitrogen oxidation as a function of pH for non-adapted culture (2).	17
5	Relative rate of reaction in the laboratory filter as a function of the percent stoichiometric oxygen requirement (2).	18
6	Schematic flow diagram of Union Sanitary Plant No. 3.	22
7	Schematic diagram of the submerged filter with preoxygenation and recycle.	24
8	Percent ammonia removal versus time during filter start-up (preoxygenation with recycle - 60 minute detention time).	36
9	Nitrogen profile through filter (preoxgenation with recycle of 2.75; 60 minute detention time; influent NH_3-N conc. of 10.6 mg/l).	38
10	Profile of dissolved oxygen, ammonia, and nitrite in the preoxygenation filter (60 minute detention time).	39
11	Rhodamine dye tracer study of the preoxygenation filter.	43
12	Recovery of preoxygenation filter from anaerobic and idle aerobic conditions.	51
13	Percent ammonia removal versus time during start-up (Bubble oxygenation system - 60 minute detention time).	53
14	Profile of DO, alkalinity, NH_4^+-N, and NO_2^--N concentrations in the bubble oxygenation filter (60 minute detention time).	55

		Page
15	Recovery of bubble oxygenation filter from anaerobic and no feed conditions (30 minute detention time).	57
16	Ammonia nitrogen variations over 24-hour periods.	58
17	Comparison between ammonia removal efficiencies obtained in the laboratory and in the field studies with the preoxygenation filter.	64
18	Flow through submerged filter with recycle.	66

TABLES

		Page
1	Results of preoxygenation with single pass operation.	12
2	Results of preoxygenation with recycle operation.	14
3	Results of bubble oxygenation operation.	19
4	Design parameters for Union Sanitary District No. 3.	23
5	Summary of analytical errors.	31
6	Typical characteristics of treated effluent from Union Sanitary District Plant No. 3.	34
7	Ammonia nitrogen removal in the preoxygenation filter.	37
8	Typical influent and effluent nitrogen concentrations in the preoxygenation filter.	37
9	BOD removal in the preoxygenation filter.	41
10	COD removal in the preoxygenation filter.	41
11	Suspended solids removal in the preoxygenation filter.	41
12	Suspended solids balance in the preoxygenation filter.	45
13	Suspended solids accumulation in the preoxygenation filter based on a COD, nitrogen and oxygen balance.	46
14	Suspended solids (S.S.) accumulation based on trapped S. S. and S. S. production due to nitrification and the oxidation of organic matter.	48
15	Correlation between carbonaceous oxygen demand and BOD_5 removal.	49
16	Ammonia nitrogen removal in the bubble oxygenation filter.	54
17	Typical influent and effluent nitrogen concentrations in the bubble oxygenation filter.	54
18	BOD, COD and suspended solids removal in the bubble oxygenation filter.	54
19	Effluent nitrogen forms remaining after nitrification.	60
20	Comparison of laboratory and field results.	65
21	Estimate of filter cost.	71

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SECTION I

CONCLUSIONS

1. Successful nitrification of secondary activated sludge plant effluent has been demonstrated in this field study with a laboratory scale submerged rock filter using pure oxygen.

2. The submerged filter not only achieved nitrification, but also acted as an efficient polishing device to reduce BOD, COD, and suspended solids from the activated sludge plant effluent.

3. The efficiency of ammonia nitrogen oxidation was mainly a function of detention time (based on void volume and the untreated influent flow rate) and the fraction of nitrifying bacteria relative to other suspended solids in the filter.

4. The oxygen required for nitrification can be added either by preoxygenation of the wastewater at one atmosphere partial pressure just before entering the filter or by direct bubbling of oxygen into the filter.

5. For the preoxygenation system the following conclusions can be drawn:

   a. Recycle of nitrified effluent is required for the preoxygenation system because of the limited solubility of oxygen in water; the minimum required recycle ratio (recycle flow rate divided by untreated wastewater flow rate) is a function of temperature and wastewater BOD and ammonia concentrations.

   b. An influent ammonia nitrogen concentration of 14.3 ± 2.6 mg/l was reduced 93 ± 3 percent with a recycle ratio of 2.75 and a detention time of 60 minutes at temperatures ranging from 21 to 27 °C.

   c. Under the above conditions, influent BOD_5 values of 35 ± 6 mg/l were reduced about 86 percent to values of 5 ± 3 mg/l, while influent suspended solids concentrations of 27 ± 3 mg/l were reduced about 87 percent to values of 3.5 ± 4 mg/l.

   d. In order to prevent clogging, backwashing twice per week at rates (gravity draining) of 6 to 20 gal/ft^2/min were satisfactory with 60-minute detention-time operation.

   e. Clogging became a problem even with the above backwashing procedure at higher suspended solids loading rates which occurred at detention times of 30 to 40 minutes.

f. Although many suspended solids forming and destroying reactions take place within the filter, the rate at which suspended solids accumulate in the filter is mainly a function of secondary effluent flow rate and suspended solids concentration.

6. For the bubble oxygenation system the following conclusions can be drawn:

   a. The nitrification performance of the bubble oxygenation system at a given detention time was nearly equivalent to the preoxygenation filter, except the starting times and recovery times after adverse conditions were somewhat longer.

   b. Because of turbulence caused by rising bubbles, BOD_5 and suspended solids removals were lower and more variable than in the preoxygenation system; at a 60-minute detention time the BOD_5 removal was 74 ± 7 percent and suspended solids removal was 48 ± 40 percent.

   c. Clogging problems were less severe than in the preoxygenation system because the rising bubbles prevented a heavy suspended solids increase in the filter pore spaces; partial gravity draining once per week at rates of 6 to 20 gal/ft^2/min were sufficient to prevent clogging.

7. Oxygen consumption within the filter equals about 4.5 pounds per pound of ammonia nitrogen removed plus about 1 pound per pound of BOD_5 removed.

8. Suspended solids interfere with the nitrification process so that at a given detention time, increased suspended solids concentrations in the influent resulted in decreased efficiency of ammonia removal.

9. Sufficient alkalinity must be present in the secondary effluent in order to prevent an unacceptable drop in pH during treatment; measured alkalinity decreases during nitrification were close to the theoretical value of 7.1 mg/l per mg/l of ammonia nitrogen oxidized.

10. Estimated construction, operation, and maintenance costs for plants ranging in capacity from 100 to 5 mgd, based on a 5.5 percent interest rate and a 20-year design period, range between 2.8 and 4.8 cents per 1000 gal for a preoxygenation filter and between 2.2 and 3.9 cents per 1000 gal for a bubble oxygenation filter.

SECTION II

RECOMMENDATIONS

A submerged filter with a capacity of about 5,000 or 10,000 gallons per day should be constructed and operated to demonstrate the feasibility of this process for full-scale operation and to develop more adequately the technology required to operate and maintain the process. Both the preoxygenation filter with recycle and the bubble oxygenation systems should be evaluated as each has different operational characteristics which may be more advantageous for certain treatment requirements. The following should be sought during this demonstration:

1. Technology should be developed for minimizing the potential clogging problem, such as use of large rates of air flow to dislodge solids, use of high backwash rates for disloding and removing solids, or use of tall filters to promote the rate of downflushing from the filter.

2. An optimum economical method to interject oxygen into the wastewater for the preoxygenation system should be sought.

3. Possible methods of reducing oxygen requirements in direct bubbling systems should be evaluated such as recycle of oxygen, staging of submerged filter systems, and increasing filter heights.

4. An evaluation of the effect of filter height on the operational characteristics of the filter should be made.

5. A determination of the optimal distribution system for influent wastewater, and collection system for treated wastewater should be made.

6. The advantages of using filter stages should be explored for the following reasons:

   a. To aid in obtaining optimal oxygen transfer efficiency.

   b. To investigate the possibility of operating a bubble oxygenation filter with high effluent dissolved oxygen concentration to be followed by a single pass preoxygenation filter for obtaining greater efficiency of nitrification, and suspended solids and BOD removal.

SECTION III

INTRODUCTION

Processes for oxidation and/or removal of nitrogen compounds from wastewaters are needed for several reasons. Compounds of nitrogen can in certain cases increase the rate of eutrophication of rivers and lakes. Nitrate-nitrogen, NO_3^--N, has been implicated as a cause of methemoglobinemia in infants. Ammonia-nitrogen, NH_3-N, may be undesirable because of its reactions with chlorine. Perhaps most important, reduced nitrogen compounds can exert a significant oxygen demand on receiving waters through biological nitrification.

Controlled biological nitrification in a treatment system is one method by which reduced compounds of nitrogen (NH_3-N and NO_2^--N) can be oxidized to nitrate nitrogen prior to waste discharge in order to reduce some of the above adverse effects. It can also be used as a first step in the nitrification-denitrification biological process for removal of nitrogen from wastewaters. Nitrification of wastewaters can be achieved using the activated sludge or trickling filter processes. In order to obtain nitrification in the activated sludge process, a long biological solids retention time or sludge age (θ_c) is required, especially for low temperature operation. This is sometimes difficult to achieve. The trickling filter is more efficient at retaining microorganisms, but suffers because there is no direct control over the retention time of the wastes in the filter. Again, at low temperatures the process is difficult to maintain (20).

A recognition of the above limitations led to the development of the submerged filter for nitrification. This process combines the biological solids retaining efficiency of the trickling filter with the hydraulic control of the activated sludge process. This study was conducted in order to determine the operational characteristics of the submerged filter and to ascertain its advantages and limitations. The study was conducted in two phases. The first was a laboratory evaluation of the kinetics and operational parameters of importance for filter operation. This study has been reported in detail in an August 1971 progress report (2). A brief summary of the laboratory study is included in this report for background information. The second phase was a study of the operational characteristics of the submerged filter while operating in the field and receiving the activated sludge effluent from the Union Sanitary District Plant No. 3, Union City, California. The results of this phase are reported in detail in this report.

The submerged filter consists of a bed of stones, 1 to 2 inches in diameter, through which wastewater passes in an upward direction. Organisms grow on the surfaces of the stones or in the void spaces between, and reach concentrations of several thousands mg/l, measured as total suspended solids. Conditions within the filter are relatively quiescent so that little loss of the biological solids occurs, permitting biological

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solids retention times of over 100 days. In addition, the upward and submerged flow allows good control over the hydraulic detention time.

The 20-month laboratory study of the submerged filter reported previously (2) was conducted using a synthetic waste consisting of tap water containing ammonium sulfate. In general 90 percent oxidation of 20 mg/l NH_3-N was obtained with a detention time (based on raw waste flow and filter void volume) of 30 minutes at 25 °C and 60 minutes at 15 °C. For the same percent removal, detention times of 90 and 120 minutes were required at temperatures of 10 °C and 5 °C, respectively. Oxygen was added to the waste either before it entered the filter or during passage through the filter. The process was stable and responded almost immediately to changes in temperature and flowrate without interruption of service. The filter could withstand unfavorable conditions such as lack of oxygen or low pH, for a period of several days, resuming operation when conditions become favorable.

The objectives of this field portion of the study were as follows:

1. To determine the applicability of the submerged filter to the nitrification of a domestic activated sludge plant effluent.
2. To evaluate a recycle system with prior oxygenation of the waste before entering the filter.
3. To evaluate oxygen addition by direct bubbling into the filter.
4. To determine the influence of activated sludge effluent suspended solids and carbonaceous BOD on the nitrification ability of the filter.
5. To determine the applicability of laboratory results to field conditions of operation.
6. To obtain an estimate of the cost for treatment.

SECTION IV

BACKGROUND

This section contains basic information for this study. It also contains a general description of the nitrification process and the results of the original laboratory study of nitrification in the submerged filter (2).

Nitrification

Nitrifying Organisms and General Growth Factors. Nitrification is a two stage biological process. A group of autotrophic bacteria represented by the genus Nitrosomonas, employ nitrification of ammonium (NH_4^+) as their sole source of energy. In the presence of oxygen, ammonia is converted of nitrite (NO_2^-) plus water and hydrogen ions, with an energy yield of approximately 65 kilocalories/mole:

$$NH_4^+ + 3/2\ O_2 \xrightarrow{\text{Nitrosomonas}} NO_2^- + 2H^+ + H_2O \qquad (1)$$

The second specialized group of microorganims represented by Nitrobacter are capable of extracting additional energy by oxidation of the nitrite, generated by Nitrosomonas, to nitrate yielding 17.5 kilocalories per mole:

$$NO_2^- + 1/2\ O_2 \xrightarrow{\text{Nitrobacter}} NO_3^- \qquad (2)$$

The nitrifying bacteria employ the energy released from both of the above reactions for assimilation of cell carbon (from carbon dioxide) as well as for cell maintenance.

If $C_5H_7O_2N$ is assumed as the empirical cell formulation for nitrifying bacteria, then the assimilation reaction can be represented by the following equation:

$$5\ CO_2 + NH_4^+ + 2H_2O \longrightarrow C_5H_7O_2N + 5\ O_2 + H^+ \qquad (3)$$

Equations 4 and 5 describe the overall reactions of nitrification and assimilation and were approximated by combining Equations 1, 2, and 3 together with cellular yields reported for nitrifying bacteria (3).

$$\text{Nitrosomonas} \quad 55\ NH_4^+ + 5\ CO_2 + 76\ O_2 \longrightarrow C_5H_7O_2N + 54\ NO_2^- + 52\ H_2O + 109\ H^+ \qquad (4)$$

$$\text{Nitrobacter} \quad 400\ NO_2^- + 5\ CO_2 + NH_4^+ + 195\ O_2 + 2\ H_2O \longrightarrow C_5H_7O_2N + 400\ NO_3^- + H^+ \qquad (5)$$

On this basis, nitrification of 20 mg/l of ammonium nitrogen would produce only about 3 mg/l of Nitrosomonas and about 1/2 mg/l of Nitrobacter, while consuming 85 mg/l of dissolved oxygen and producing 2 moles of hydrogen ion for each mole of ammonium oxidized. The cells would contain approximately 2 percent of the original ammonium nitrogen (4).

The production of hydrogen ions during nitrification will result in a decrease in alkalinity of 7.13 mg/l as $CaCO_3$ for every 1 mg/l NH_3-N oxidized to NO_2^-. In order to maintain a pH above 6.0 some alkalinity must remain in solution after nitrification has occurred. Calculations (2) involving carbonic acid equilibria show that at an initial pH between 7.0 and 8.5, the ammonia nitrogen concentration that can safely be oxidized is roughly equal to 1/10 of the alkalinity of the water. Therefore, in a water with an alkalinity of 200 mg/l as $CaCO_3$, approximately 20 mg/l NH_3-N could be oxidized while maintaining a pH above 6.0. If sufficient alkalinity is not present, then lime or some other alkaline material must be added. In a subsequent part of this section the effect of a pH value of 6.0 on bacterial growth will be discussed.

Stoichiometry (Equation 1) indicates that 4.57 mg of oxygen is required for complete oxidation of 1 mg NH_3-N. Equations 4 and 5, which include the effects of CO_2 assimilation to cells (Equation 3), predict a reduced requirement of 3.9 mg of oxygen per mg NH_3-N oxidized. The actual oxygen requirement in practice will be between these values because of long cell residence time and organism decay, which tends to reduce the actual cell yield below that given by Equations 4 and 5.

It has been found that nitrification will occur in the presence of high concentrations of organic matter (50-110 mg/l BOD) if oxygen is not limiting. However, it can be expected that a high relative carbonaceous BOD concentration in the feed to a biological treatment system will decrease the percentage of nitrifying organisms present within a given biomass, and as a result, affect the time necessary to achieve complete nitrification (5).

Kinetics of Nitrification in the Submerged Filter. Monod (6) and Michaelis and Menton (7) have mathematically formulated a function for describing the maximum utilization rate of substrate by bacteria similar to the following:

$$-\frac{dS}{dt} = \frac{kSX}{K_s + S} \qquad (6)$$

where: $-\frac{dS}{dt}$ = rate of substrate utilization, mass/vol-time.

k = maximum rate of substrate utilization per mass of microorganisms, mass/time-mass of active microbes.

K_s = the "half-velocity coefficient," the substrate concentration at which the rate of reaction is one-half the maximum rate, mass/vol.

S = concentration of rate-limiting substrate surrounding the cell, mass/vol.

X = concentration of active microorganisms, mass/vol.

The kinetic coefficients k, K_s, and X vary depending on the substrate, the particular organisms under study, and the conditions under which they are grown. The maximum rate is thought to occur when the cellular enzyme systems have become saturated with substrate.

Any homogeneous system in which substrate and microorganisms are equally distributed throughout the reactor volume will operate in accordance with the above equation. An example is the activated sludge process.

However, in the submerged filter diffusion is also an important variable. Since a definite interface exists between the microorganisms, attached to the media surface, and the liquid phase, substrate must move across this interface in order to be utilized.

Figure 1 is a conceptual diagram of how the concentration of substrate might decrease within layers of biological solids attached to the media. The substrate concentrations are defined as follows:

S_b = substrate concentration in the bulk liquid phase outside the bio-film.

S_i = substrate concentration at the liquid-film interface.

S_f = substrate concentration in the film.

S_o = substrate concentration at the film-media interface.

Diffusion into the biological mass as well as diffusion through the interface most likely control the rate of substrate utilization. At equilibrium the rate of substrate movement across the interface equals the rate of substrate utilization by the bacterial film. Haug and McCarty (2) concluded that for any given media an active bio-film thickness of approximately 1 mm will permit the maximum possible rate of nitrification at 15 °C with an initial ammonium nitrogen concentration of 20 mg/l.

In the submerged filter, the diffusion of substrate materials is quite complex. Figure 2 shows the hypothetical situation existing in the submerged filter during nitrification. Since CO_2 and O_2 are non-electrolytes, their diffusion coefficients are not influenced by the presence or absence

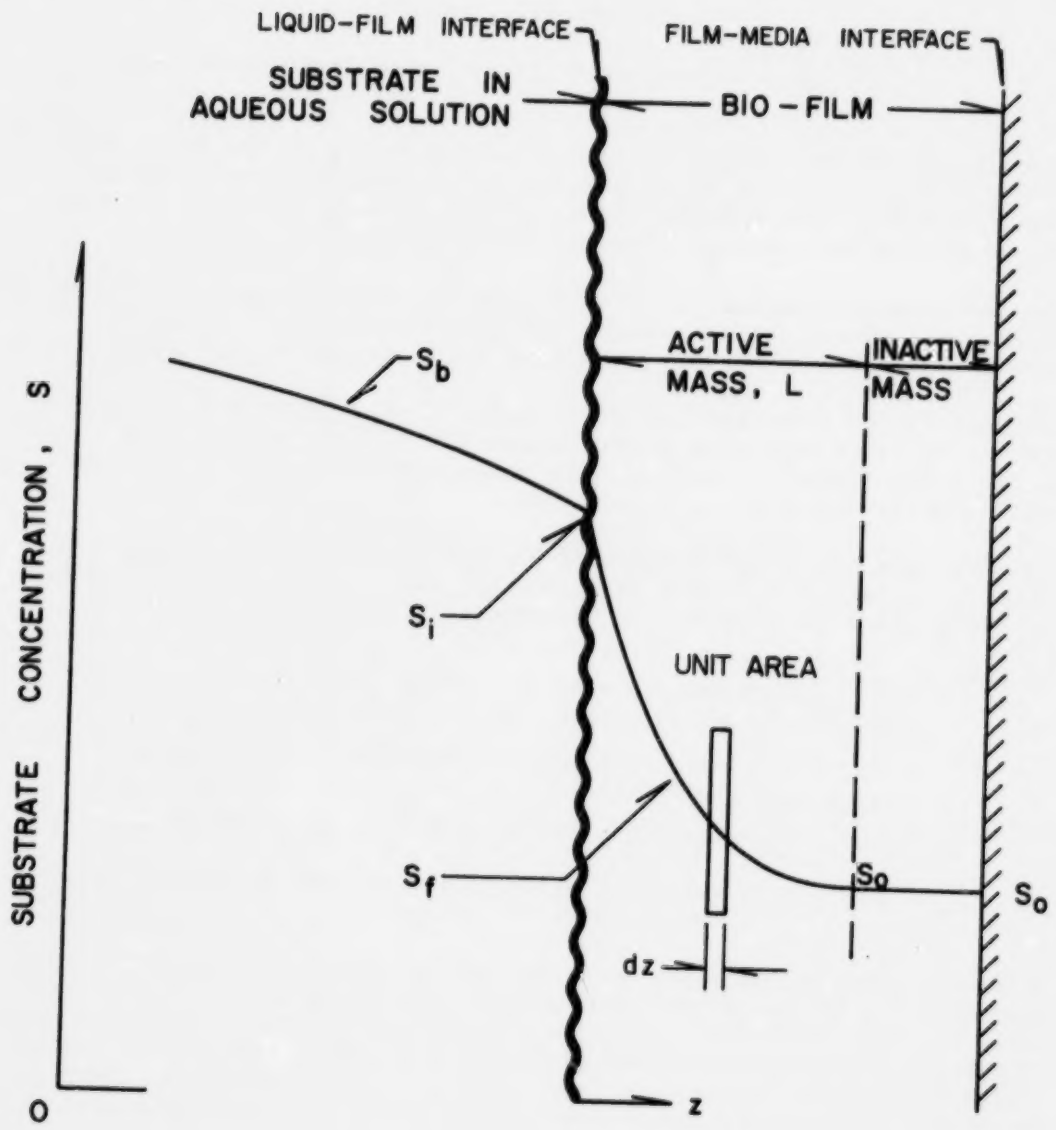

Figure 1. Heterogeneous system composed of substrate in aqueous solution and microbial population in biological film.

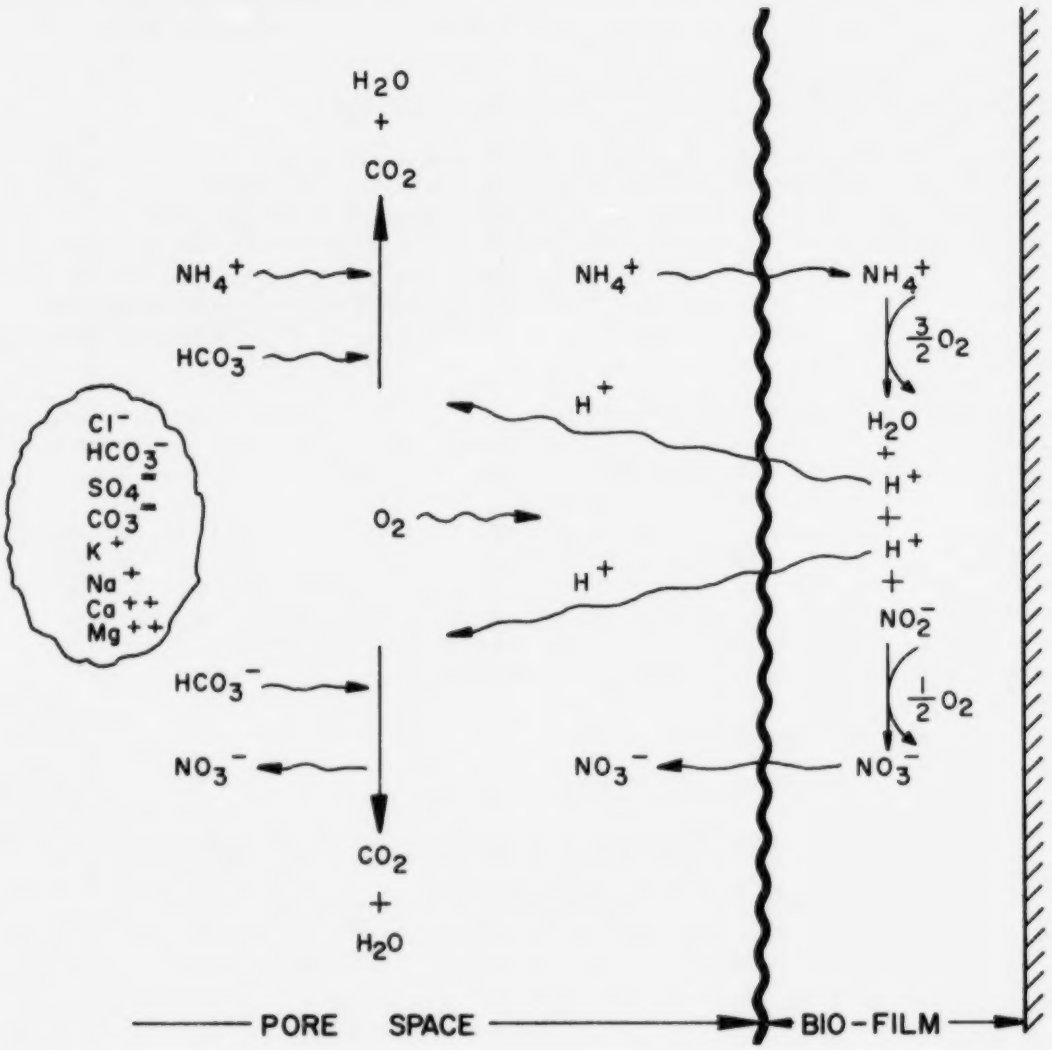

Figure 2. Diffusion of major ions during nitrification in the submerged filter (2).

of other materials. The ammonium, nitrite, nitrate and hydrogen ions all are electrolytes. These ionic flows involve moving charges and thus each influences the movement of the others.

It should be noted that the diffusion coefficient for oxygen in water is approximately 40 percent higher than for ammonium at the same temperature. Therefore, oxygen when supplied in a stoichiometric amount, should not limit the rate of ammonium oxidation in a biological film.

Results of Laboratory Studies on the Submerged Filter

The detailed results from the laboratory study were presented previously (2). A brief summary is presented in the following for background. The submerged rock filters used in the laboratory study were the same as used in this field study. The reader may benefit from previewing Section V, which contains details of the pilot plant apparatus, before reading this section. The three systems discussed are the preoxygenation system with single pass operation and recycle operation, and the bubble oxygenation system.

Preoxygenation With Single Pass Operation. In this system, the synthetic waste ammonium concentration was arbitrarily limited to the amount which could be oxidized by the quantity of oxygen that could be dissolved in the waste at one atmosphere of pressure. For example, at 20 °C, the solubility of oxygen is 43.7 mg/l, and not more than 9.6 mg/l of ammonia nitrogen can be oxidized with this concentration. The results of single-pass operation with varying temperatures and detention times are listed in Table 1 for various ammonium concentrations used. At 25 °C, 90 percent removal was possible in slightly over 15 minutes, while at 15 °C 90 percent removal was possible in 30 minutes.

TABLE 1

RESULTS OF PREOXYGENATION WITH SINGLE PASS OPERATION (2)

Temp. °C	Detention Time(min.)*	Influent NH_3-N(mg/l)	Average Percent NH_3-N Removal
25	7.5	8.0	70
	15	7.9	75-89
	30	8.0	95
15	15	9.7	87
	30	9.9	91
10	30	10.1	88
5	30	9.7	66
	60	12.2	75
	120	11.9	92

* Based on the influent waste flow rate and the filter void volume.

The following rate equation was empirically found to fit the decrease in NH_3-N concentration with time in the filter (-dS/dt):

$$\text{Rate} = -\frac{dS}{dt} = aS^b$$

$$\log -\left[\frac{dS}{dt}\right] = \log(a) + b \log(S) \qquad (7)$$

where: a = rate constant

b = order of reaction

An analysis of the results from the submerged filter operation in the laboratory resulted in the following equations:

Temp. °C	Equation	
25	$-\frac{dS}{dt} = 2.59\left[\frac{S}{10}\right]^{1.48}$	(8)
15	$-\frac{dS}{dt} = 1.15\left[\frac{S}{10}\right]^{0.93}$	(9)
10	$-\frac{dS}{dt} = 0.99\left[\frac{S}{10}\right]^{1.25}$	(10)
5	$-\frac{dS}{dt} = 0.38\left[\frac{S}{10}\right]^{1.10}$	(11)

In these equations the rate is given in terms of mg/l NH_3-N oxidized per minutes (mg/l-min) and the concentration, S, as mg/l NH_3-N. The order of reaction constant, b, varied from a value as low as 0.9 to a value as high as 1.5 depending on the degree of bio-film development throughout the filter. An intermediate value of 1.2 was used to formulate a general equation for temperatures between 5 and 25 °C:

$$-\frac{dS}{dt} = (0.11\ T - 0.20)\left[\frac{S}{10}\right]^{1.2} \qquad (12)$$

where T = Temperature in °C

This generalization was allowable because the rate constant, a, varied linearly with temperature. The above equations are only applicable to laboratory operation of the filters using a wastewater containing no suspended solids. The data collected from the bubble oxygenation system approximated the predictions of the above equations.

Preoxygenation With Recycle Operation. In a preoxygenation system at one atmosphere, recycle operation is required for any waste in which

the ammonium concentration is greater than can be removed in a single pass (Figure 3). The recyle ratio (ratio of recycle flow to raw wastewater flow) must be adjusted to provide enough oxygen in the filter for the oxidation of the ammonia nitrogen in the wastewater. At lower temperatures less recycle is needed because oxygen is more soluble. Data was collected at influent concentrations of 20 to 30 mg/1 NH_3-N. With recycle, 90 percent oxidation of 20 mg/1 NH_3-N was obtained with a detention time (based on raw waste flow) of 30 minutes at 25 °C and 60 minutes at 16 °C (Table 2). Detention times between 60 and 120 minutes would be required in the temperature range of 10 to 5 °C.

TABLE 2

RESULTS OF PREOXYGENATION WITH RECYCLE OPERATION (2)

Temp. °C	Recycle Ratio +	Detention Time(Min.)*	Initial NH_3-N (mg/1)	Average Percent NH_3-N Removal	Effluent Dissolved Oxygen (mg/1)
25	1.7	30	20	90	7.2
	1.7	45	20	95	6.8
	1.6	60	20	95	3.2
16	1.1	45	20.3	86	6.9
	1.1	60	20.3	91	6.5
	2.0	60	20.2	93	15.3
	3.0	60	20.2	95	22.2

* Based on the raw waste flow rate and the filter void volume.
\+ Recycle ratio = recyle flow rate/raw waste flow rate.

Equations 8 through 11 can be integrated to determine the detention time required for a given degree of NH_3-N oxidation. Multiplying the resulting detention time by (1 + R) gives the overall required detention time (t_o = V/Q) based on the raw waste flow rate (Q) and filter void volume (V).

$$t_o = \left[\frac{10^b}{a(b-1)}\right]\left[\frac{1}{S_e^{(b-1)}} - \frac{1}{S_i^{(b-1)}}\right](1+R) \quad b \neq 1 \qquad (13)$$

where t_o = detention time required to reduce the NH_3-N concentration from S_w to S_e.

S_w = NH_3-N concentration in the raw waste water.

S_i = influent NH_3-N concentration to the filter after mixing of raw waste water and recycle flows:

$$S_i = \frac{S_w + RS_e}{1 + R} \qquad \text{(See Figure 3)}$$

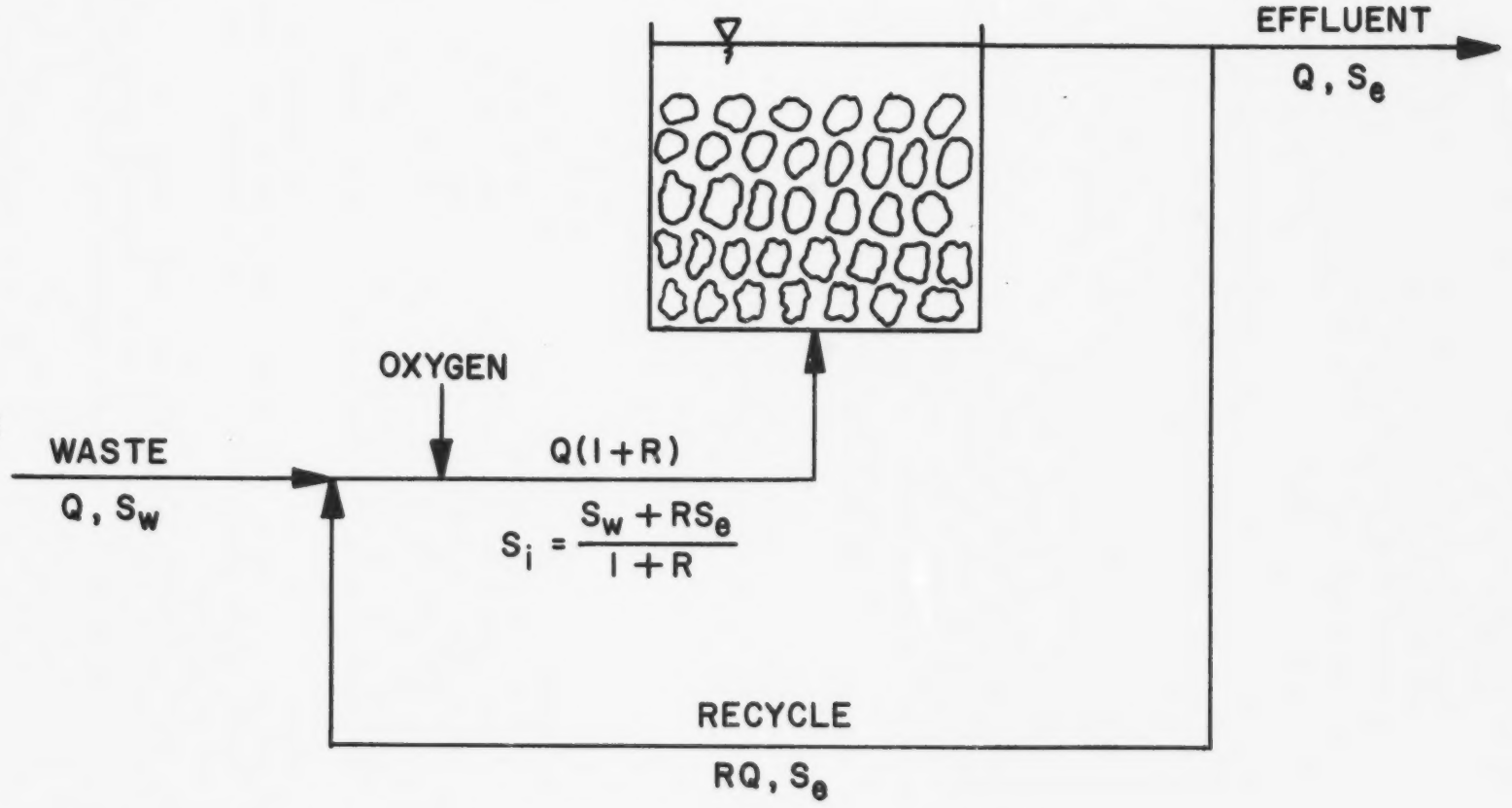

Figure 3. Flow rates for submerged filter with recycle.

S_e = effluent NH_3-N concentration from the submerged filter.

R = recycle ratio necessary to reduce concentration S_w to a level stoichiometric with the filter influent oxygen concentration.

a = rate constant

b = order of reaction

Using average values of the rate constants from Equation 13, the required detention time, t_o, can be described over the temperature range from 5 to 25 °C:

$$t_o = \frac{79(1 + R)}{0.11\ T - 0.20} \left[\left(\frac{1}{S_e} \right)^{0.2} - \left(\frac{1}{S_i} \right)^{0.2} \right] \qquad (14)$$

Based on this equation 90 percent removal of 20 mg/l NH_3-N should be obtained with detention times of about 20 and 30 minutes at temperatures of 25 and 15 °C respectively. This range of performance agrees reasonably well with that observed in the recycle studies presented in Table 2. At any temperature a curve of ammonia nitrogen removal efficiency versus detention time can be plotted making use of Equation 14 and an efficiency computation.

Operational Characteristics With Preoxygenation. The nitrification rate in the submerged filter decreased when the pH fell below 6.6 (Figure 4) (2). However, the nitrifying bacteria acclimated to the lower pH conditions so that after a period of operation the rates of oxidation at pH 6.0 approximated those normally encountered at pH 7.0 or higher. Below pH 6.0 nitrification rates decreased rapidly and acclimation was not so successful. These results suggest that if nitrification is desired, the submerged filter should be operated to maintain a pH above 6.0. Thus, if the natural alkalinity of a waste is low, additional alkalinity must be added to prevent the pH from dropping below 6.0. It should be noted that Wild, Sawyer, and McMahon (5) found different effects of pH on the kinetics in the activated sludge process for nitrification. They observed that nitrification was optimal at pH 8.4; 3/4 optimal at pH 7.5 and 9.3; and 1/2 optimal at pH 7.0 and 9.8. The effects of pH may thus be somewhat different in the submerged filter and the activated sludge system, however their studies were with non-acclimated organisms.

A dissolved oxygen concentration of up to 60 mg/l in the filter did not inhibit nitrification. However, at oxygen concentrations lower than the stoichiometric oxygen requirement the rate of nitrification was lower than normal (Figure 5) (2).

Studies were also conducted to determine the effect of anaerobic conditions and periods with no substrate feed on the operation of the submerged filter. After 7 days of anaerobic operation the filter returned

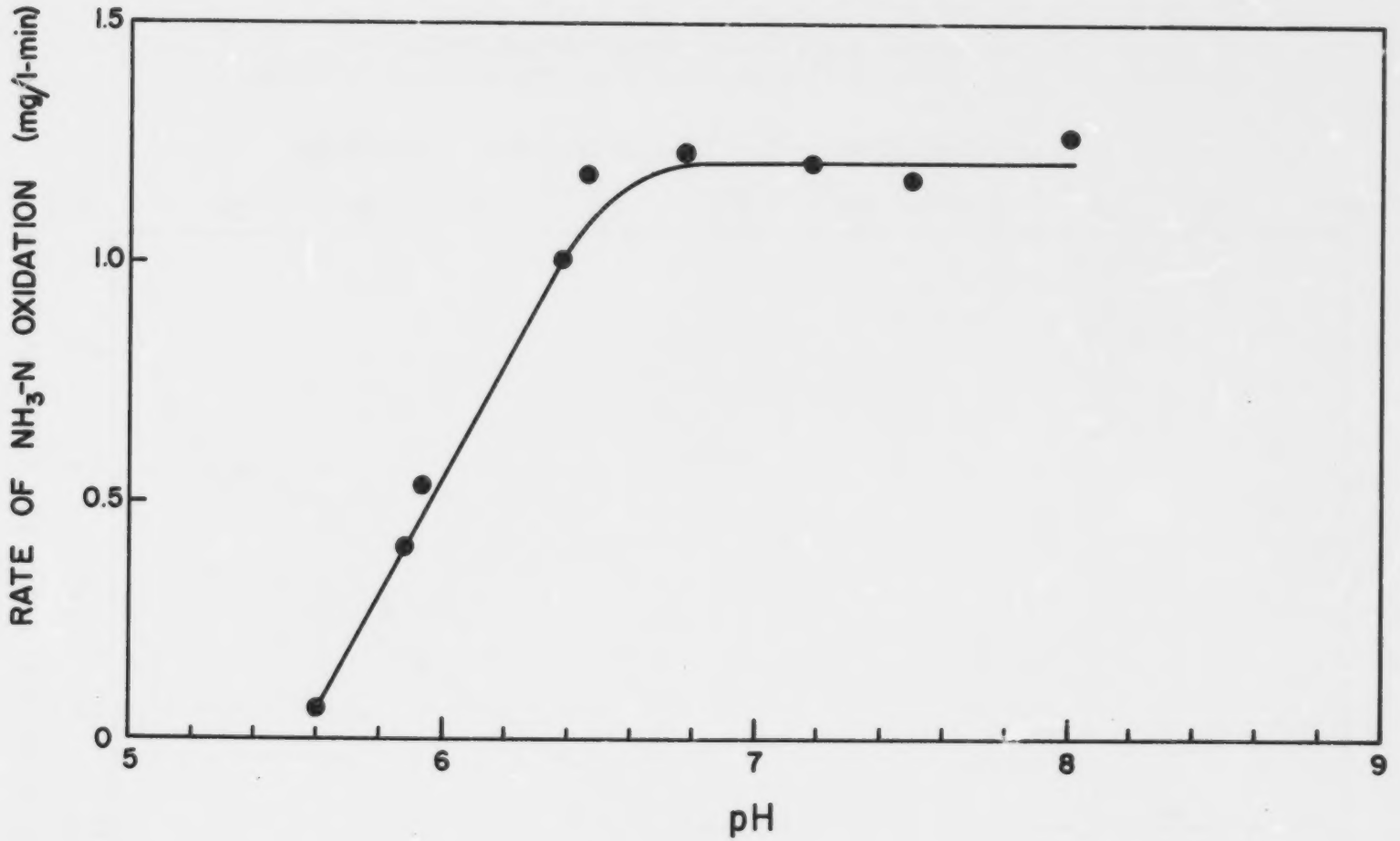

Figure 4. Rate of ammonia-nitrogen oxidation as a function of pH for non-adapted culture (2).

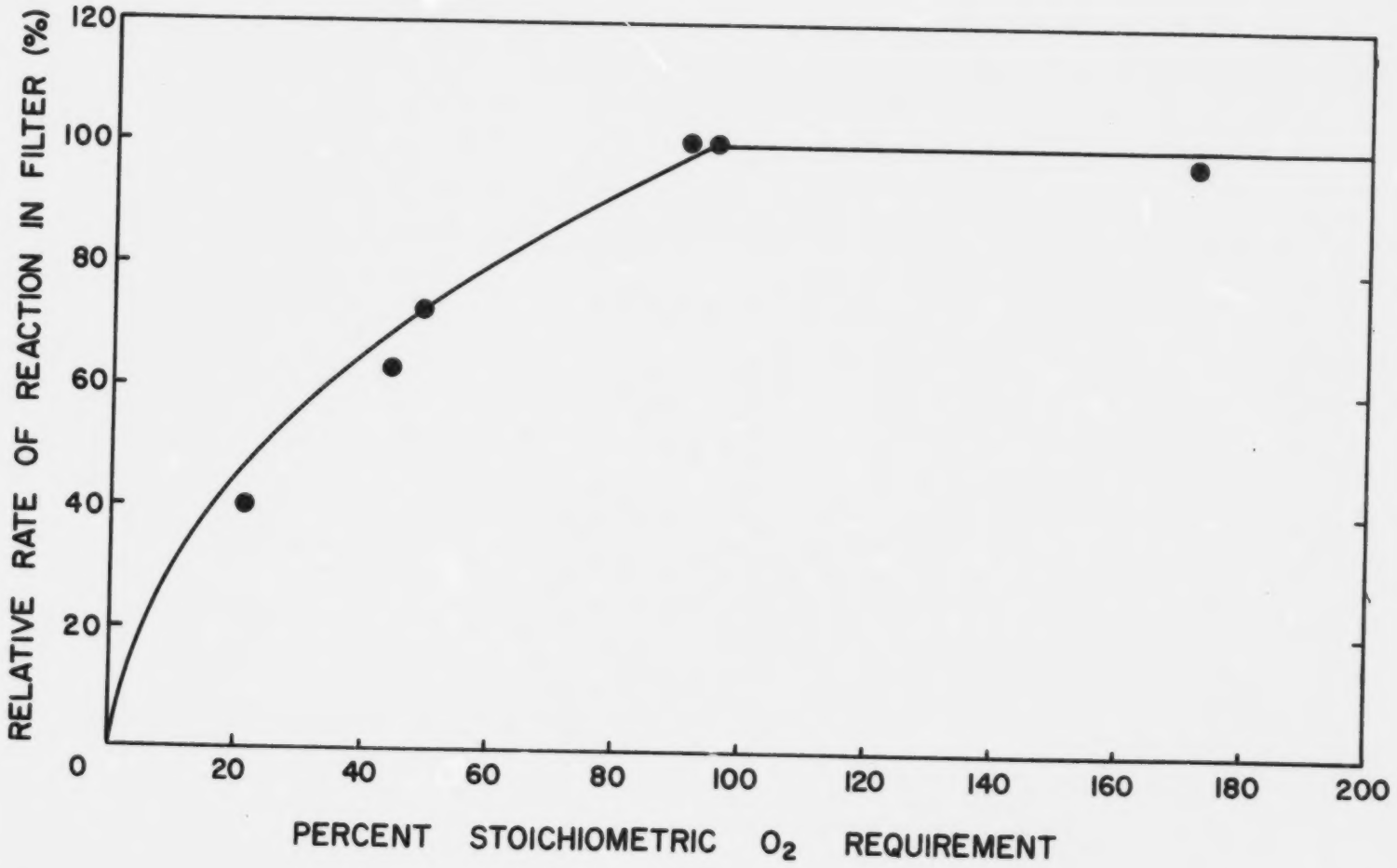

Figure 5. Relative rate of reaction in the laboratory filter as a function of the percent stoichiometric oxygen requirement (2).

to 50 percent of normal oxidation rate within 2 hours and 99 percent within 4 days.

Upon the completion of the laboratory submerged filter study, the suspended solids were removed for analysis. The mixed liquor suspended solids concentration was 4800-5600 mg/l (based on the void volume). An average of 78 percent of these solids was volatile. A gradient of suspended solids existed in the filter and many solids were not attached to rocks, but trapped between them. The largest concentration of bacterial cells was at the bottom of the submerged filter along with the highest NH_3-N concentration. Nearly all of the suspended biological solids produced during treatment were held in the filter, so that the solids concentration increased as bacterial growth occurred. Initially increased biological growth led to an increased degree of oxidation. However, further increases eventually led to short-circuiting and decreased efficiency. The hydraulic head loss through the filters was always quite small and at no time greater than 5-6 inches of water, even at flow rates as high as 680 ml/min (1.09 gal/ft^2) and in filters which had become clogged with biological solids. At lower flow rates the head loss was only 1 or 2 inches of water.

Bubble Oxygenation. Bubble oxygenation can supply enough oxygen to oxidize a high concentration of ammonia in a single pass through the filter. The ascending bubbles prevented biological solids build-up in media in the laboratory study. The lack of clogging in the void spaces and the more uniform development of bio-film compensated for a decrease in suspended solids necessary for a given ammonium oxidation rate. The preoxygenation system seemed to follow plug flow kinetics, whereas, the bubble oxygenation system tended to be completely mixed. In order to avoid oxygen from becoming rate limiting, the dissolved oxygen concentration needed only to be stoichiometric with the actual NH_3-N concentration in the filter (Table 3).

TABLE 3

RESULTS OF BUBBLE OXYGENATION OPERATION

Temp. °C	Detention Time(min.)*	Influent NH_3-N mg/l	Percent NH_3-N Removal	Effluent Dissolved Oxygen mg/l
22	30	19.7	89	22
	60	19.7	95	14
10	30	21.6	51	31
	60	20.0	86	23
	90	21.6	95	31
5	90	20.5	79	34
	120	20.7	93	-

* Based on the influent waste flow rate and the filter void volume.

Stable nitrification was observed over a six month study period. With an influent concentration of 20 mg/l NH_3-N, oxidation was approximately 90 percent complete with a detention time of 30 minutes at 22 °C, 60 minutes at 10 °C and between 90-120 minutes at 5 °C (Table 3). Performance was equivalent to that observed using preoxygenation and recycle of effluent. Effluent nitrite nitrogen concentrations were somewhat higher than the 1 to 2 mg/l characteristically observed with preoxygenation.

SECTION V

EXPERIMENTAL PROCEDURES

In this section a description is given of the submerged filter pilot plant used in the field study and of the full-scale activated sludge plant, the effluent from which was used as the feedwater for the pilot plant. Also set forth are the operating and maintenance procedures and the analytical methods used.

The Full-Scale Wastewater Treatment Plant Preceding the Pilot Plant Facilities

The field study was conducted at the Union Sanitary District Wastewater Treatment Plant No. 3 located in Union City, Alameda County, California. The final effluent from this plant is discharged to a slough which flows into the east side of South San Francisco Bay. A flow diagram for this activated sludge plant and a list of unit process design values are shown in Figure 6 and Table 4, respectively.

The influent municipal wastewater is comminuted with a barminutor and then pumped into a vacuator which provides the equivalent of primary treatment by employing both flotation and settling. Next are four aeration tanks which can be operated in series or parallel; with step aeration; or with sludge reaeration (contact stabilization). During this study only two of the tanks were operated and were connected in series. The mixed liquor suspended solids (MLSS) concentration in the aeration tank was usually in the range of 3000-3700 mg/l. Continuous sludge returning is accomplished by the use of uptake pipes along the final clarifier mechanism arms. Sludge wasting is accomplished separately from the center pit of the clarifier floor. After clarification the effluent is chlorinated.

The waste activated sludge is discharged into the influent sewage and is removed in the vacuator. The digestion system consists of a heated and mixed primary digester and an open lagoon which acts as the secondary digester. The overflow from the lagoon is discharged into the influent sewage and the digested sludge is periodically pumped to the sludge beds.

The influent for the submerged filter pilot plant was pumped continuously from a channel just after the final clarifier but before chlorination.

Pilot Plant Apparatus

Submerged Filter Design. Two submerged filters from the previous laboratory study were slightly modified to use in this field study. The modifications consisted of enlarging influent and effluent ports to help prevent clogging. Each filter consisted of a plexiglas column (Figure 7), 6 inches in outside diameter, 5.5 inches in inside diameter, and 3.5 feet

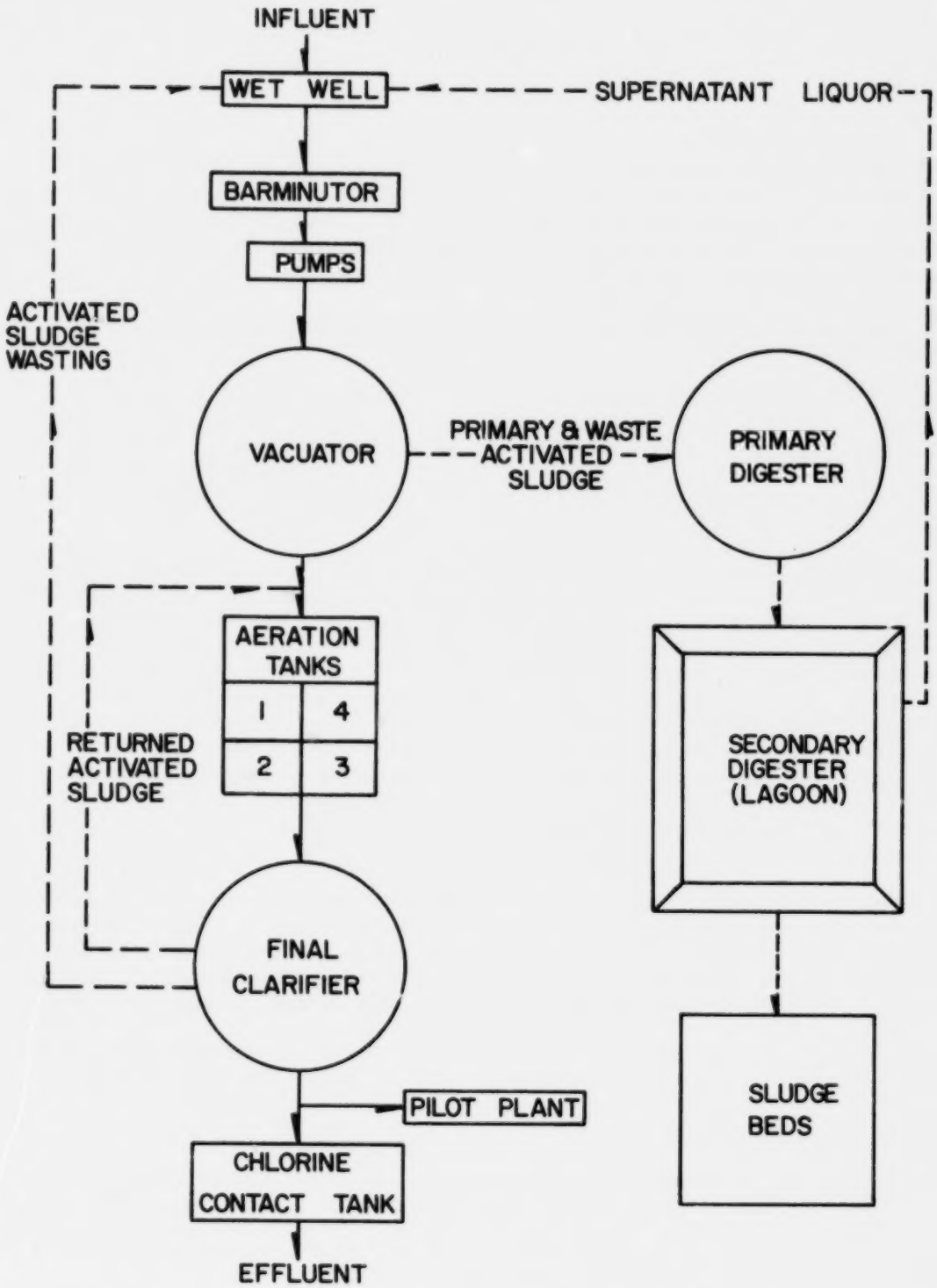

Figure 6. Schematic flow diagram of Union Sanitary Plant #3

TABLE 4

DESIGN PARAMETERS FOR UNION SANITARY DISTRICT PLANT NO. 3

Design Population Equivalent	35,000
Design Flow (mgd)	3.0
Design Peak Flow Rate (2.5 x average) (mgd)	7.5

Plant Process	Design	Actual During Study
Average Flow (mgd):	3	2.4
Vacuator:		
Volume (gal)	122,000	122,000
Overflow Rate (gpd/ft^2)	1,900	1,482
Detention Time (min)	59	72
Aeration Tanks:		
Operating Scheme	4 tanks	2 tanks (series)
BOD Loading (lbs/1000 ft^3/day)	63	65-85
Volume (gal)	670,000	335,000
Detention Time (hrs)	5.33	3.35
Detention Time with 25% sludge return (hrs)	4.28	2.57
Final Clarifier:		
Volume (gal)	385,000	385,000
Overflow Rate (gpd/ft^2)	525	415
Detention Time with 25% sludge return (hrs)	2.46	2.96
Chlorine Contact Tank:		
Volume (gal)	162,000	162,000
Detention Time (min)	77	97
Digester:		
Primary		
Volume (gal)	600,000	600,000
Detention Time (days)	30	30
Secondary (lagoon)		
Volume (gal)	330,000	330,000
Detention Time (days)	16	16

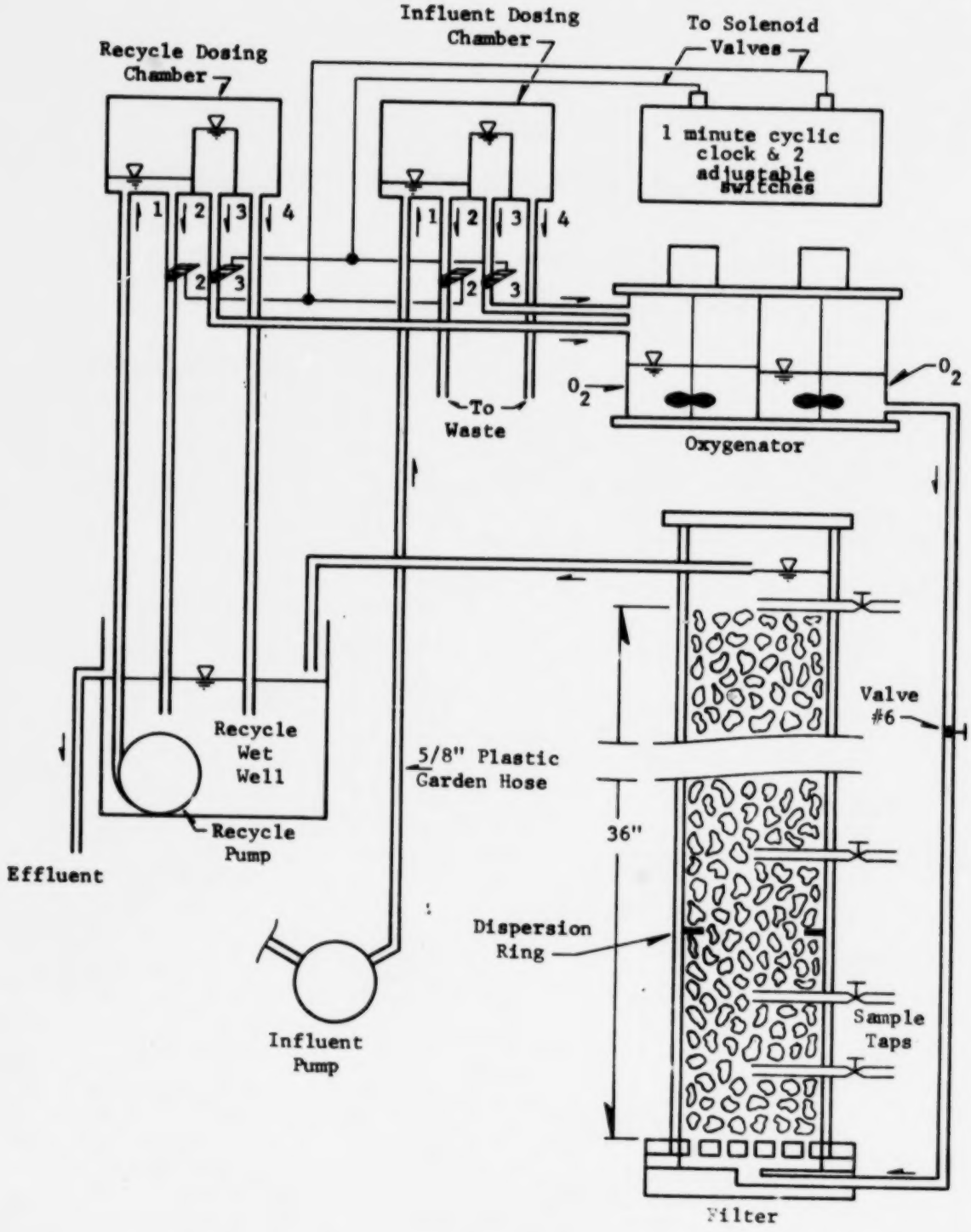

Figure 7. Schematic diagram of the submerged filter with preoxygenation and recycle.

tall. The base was constructed to disperse the waste uniformly across the bottom of the filter. Eight, five-sixteenth inch diameter holes were evenly spaced about a four-inch diameter circle. These dispersion ports extended through the bottom of the filter into a 5.5 inch diameter by 1 inch deep open space. The waste to be treated entered at the center of this open space and flowed upward through the dispersion ports.

Sample taps were located at six-inch intervals along the length of the column with an additional tap three-inches from the base. The taps extended to the center of the column, so that a more representative sample could be drawn, and were made of plexiglas tubing, one-eighth inch inside diameter, and were joined to the wall of the column with rubber grommets to give a water-tight seal.

Each column was packed with smooth quatzite stone, 1 to 1.5 inches in diameter, and filled to a depth of three feet. The stone was hand packed and graded to eliminate stones of irregular shape. This assured a uniform porosity throughout the depth of each column as well as similarity between columns. The actual void volume in each filter was determined by measuring the volume of water required to completely submerge the media. The measured void volume and the calculated porosity for each filter were as follows:

Filter	Void Volume (ml)	Porosity
No. 1 (Preoxygenation with recycle)	5482	0.392
No. 3 (Bubble oxygenation)	5440	0.388

With approximately spherical media the void space was somewhat larger where the media rested against the inside of the plexiglas column. Flat rings, three-fourths inch in width and one-sixteenth inch in thickness were placed at one-foot intervals to prevent short-circuiting through the larger void spaces. Such short-circuiting, however, could not be completely avoided as was observed with dye testing.

Feed and Oxygenation Systems. Each filter was dosed at one minute intervals with small pulses of sample. The two oxygenation methods employed were preoxygenation with recycle and bubble oxygenation.

Preoxygenation with Recycle. As mentioned earlier an NH_3-N concentration over 10 mg/l could not be completely oxidized with a single pass through the filter. Therefore, a recycle system was used to reduce the filter influent NH_3-N concentration to a level at which oxygen saturation did not limit the attainment of stoichiometric oxygen requirements.

This recycle system is portrayed in Figure 7. The effluent from the full-scale activated sludge plant final clarifier was pumped into the influent dosing chamber (hose No. 1) at a constant rate. The excess influent flow was wasted through hose No. 4. A one minute cyclic clock

with two adjustable switches controlled the two solenoid valves on hoses No. 2 and No. 3. Every minute valve No. 2 opened and all of the incoming influent was wasted, leaving a specific volume of influent in the chamber above hose No. 3. A few seconds later valve No. 3 opened and a measured volume was pulsed through the valve into the oxygenator. Valves No. 2 and No. 3 closed and then flow was again directed into the chamber over hose No. 3. This cycle was repeated once a minute. The volume of the chamber over hose No. 3 was varied by inserting objects to reduce the chamber volume. The recycle dosing chamber and the influent dosing chamber were operated at precisely the same time and in the same manner.

Once a minute a pulse of influent and a pulse of filter effluent entered the oxygenator at 1 atmosphere of pressure. The oxygenator consisted of two plexiglas chambers in series (connected by three 1/8 inch holes) both having turbine blades driven by variable speed electric motors and both being supplied with metered 99.5 percent pure oxygen through submerged ports. The oxygenator was very reliable in operation.

The influent pulses from the two dosing chambers were fairly well evened out after a 8 to 15 minute detention time (based on a combined influent and recycle flow) in the oxygenator. The still water depth in the oxygenator was normally about 2 to 5 inches, varying with the flow rate. At high flow rates gas binding in the line between the oxygenator and the filter caused flow fluctuations which in turn caused the level in the oxygenator to vary. By partially closing the influent valve No. 6 the flow remained reasonably steady. Also filter influent line air vents were used to help relieve air binding problems.

The detention time in the filter varied from 7.5 to 15 minutes per pass depending on the recycle ratio and the influent waste flow rate. The effluent from the filter entered an 18 liter recycle wet-well equipped with a submergible pump which delivered effluent up to the recycle dosing chamber. The final effluent was discharged from the recycle wet-well.

The flow rates were checked by measuring discharges from the hoses into the mixing chambers. All of the major piping was made of 5/8 inch garden hose with the appropriate male and female connectors.

Bubble Oxygenation. The bubble oxygenation filter employed a feed system exactly like the 1 minute cyclic dosing system of the preoxygenation with recycle filter. This system did not require a recycle system because stoichiometric oxygen requirements were easily obtainable. A metered flow rate of oxygen was continuously injected into the influent line with a hypodermic needle. Upon entering the filter base the oxygen bubbles rose through the 5/16 inch dispersion holes and passed-up through the rock column. Excess oxygen was vented out of the pilot plant facilities to help prevent corrosion.

Operational Procedures

Sampling. Sampling was conducted on the average of once per week over a six month period. Usually both 24 hour composite and grab samples were

taken to help verify the consistencey of the results.

Composite samples were taken of the influent and the recycle system effluent through solenoid valves connected to the influent hose No. 1 of both the influent dosing chamber and the recycle dosing chamber (figure 7). These valves were open 15 seconds out of every 30 minutes allowing 150-400 ml of sample to flow to a nearby refrigerator for storage.

Composite sampling of the bubble oxygenation filter effluent was accomplished with an effluent wet-well and a float controlled submergible pump which pumped most of the effluent to waste, allowing from 150-400 ml to be pumped to the refrigerator during each pumping cycle (20 to 60 minutes). The hose in both composite sampling systems was made of 1/4 inch plastic and latex tubing.

The field study influent composite sampler tended, at times, to collect samples with too high a suspended solids concentration. Equivalent samples were collected by a Union Sanitary District Sampler. For this reason, the District data was more accurate and was used, when necessary, for all calculations requiring an influent BOD_5 or influent suspended solids analysis.

The above sampling systems allowed the collection of reliable soluble nitrogen data. The bubbling oxygenation effluent composite sampler, however, did not collect representative samples when settleable solids were present. These samples tended to be low in suspended solids because of settling of the solids in the wet-well between pumping cycles. Therefore, suspended solids, BOD, unfiltered COD and unfiltered Organic Nitrogen data had to be evaluated from grab samples.

The refrigerated samples were kept between 40 and 50 ^{o}F. Samples were not acidified to preserve the nitrogen forms because this has been shown to cause loss of nitrite nitrogen (8).

Most tests were performed in the laboratory except dissolved oxygen, temperature, and pH which were measured in the field on grab samples.

Samples from taps along the length of the filter was taken in succession from the top of the filter to the bottom to obtain an undisturbed sample at each sampling tap. Samples of about 500 ml in volume were obtained slowly (about 3 minutes each) to prevent pulling biological solids from the filter.

Detention time studies were conducted with rhodamine dye as a tracer. The dye was injected as a pulse into the filter influent line. There was some dilution of the pulse in the influent chamber (630 ml) and exit liquid volume (760 ml) above the filter stone.

Operation and Maintenance. Once a week the apparatus, excluding the filter, was cleaned to prevent suspended solids accumulation. Some bacteria tended to grow in the other portions of the apparatus but it was not a significant population compared to that in the filters.

Backwashing. Backwashing was one of the methods used to prevent clogging in this filter. As bacteria grow and suspended solids are held within the filters, clogging eventually occurs. The solids build-up can cause short-circuiting and decreased efficiency. In order to maintain good operation, suspended solids have to be removed from the filter periodically. During suspended solids removal care was taken not to completely strip the column of bacteria.

During the first five months of operation the preoxygenation filter was backwashed by gravity through the side taps, the bottom waste taps and the influent line. Gravity backwashing rates of 6 to 20 gal/ft^2/min were attained two times a week in the 3 foot high filter. After five months of operation this filter finally plugged. Bubbling oxygen through the filter did not relieve the problem. Small passages were opened, but other passages remained clogged. Therefore another approach had to be used. Water discharged through a garden hose nozzle was directed into the top of the filter. This caused turbulence in the top foot of the filter, but it did not penetrate well to the bottom of the filter. Water from the hose nozzle was then directed into the bottom of the filter through the influent line at the rate of 20 to 40 gal/ft^2/min. This seemed to be satisfactory for unclogging the filter. This backwashing procedure was then adopted and used on a regular basis (once very 4 to 20 days). At the same time excess solids were removed twice per week by gravity draining. The filter tended to clog significantly faster with a 30 to 40 minute detention time than with a 60 minute detention time.

The bubble oxygenation filter needed less backwashing because solids were continuously lost in the effluent as a result of the turbulence caused by the rising bubbles. Gravity backwashing (partial draining) rates of 6 to 20 gal/ft^2/min were accomplished one or two times a week and were satisfactory for the control of clogging over a six month period of filter operation.

Analytical Techniques

Laboratory analyses were performed during the operation of the submerged filters for the four forms of nitrogen (organic, ammonia, nitrite and nitrate), pH, alkalinity, dissolved oxygen, temperature, suspended solids, biochemical oxygen demand (BOD), chemical oxygen demand (COD), and rhodamine dye concentration (during tracer studies).

Unless otherwise noted the analytical techniques in this section were obtained from Standard Methods for the Examination of Water and Wastewater, twelfth edition, 1965 (9).

Organic Nitrogen. Organic nitrogen was analyzed using the Kjeldahl method described on page 402 of Standard Methods (9). After ammonia was removed

by distillation, a sample was digested and subsequently distilled and titrated with standard acid. Standard Methods (9) reports a precision of ± 0.03 mg/l with a recovery of 97.5-98.6 percent over a range of 1-5 mg/l organic nitrogen.

Ammonia Nitrogen. Ammonia nitrogen determinations were made by the direct Nesslerization method described on page 389 of Standard Methods (9). Samples were clarified with zinc sulfate and sodium hydroxide precipitation and then centrifugation (4500 rpm for 4 minutes). Rochelle salts were added prior to Nesslerization. A recovery of 97-99 percent of ammonia nitrogen was reported for this test with a standard deviation of less than 0.001 mg ammonia nitrogen (9). In this study the standard deviation of two sets of 10 identical samples was 2 percent for a 15 mg/l ammonia nitrogen concentration and 5 percent for a 5 mg/l ammonia nitrogen concentration.

Nitrite Nitrogen. Nitrite nitrogen was determined by the naphthylamine hydrochloride sulfanilic acid method described on page 400 in Standard Methods (9). Samples were clarified using zinc sulfate and sodium hydroxide as in the ammonia nitrogen test described above. The precision, as standard deviation, on sewage effluents using a filter photometer, is 0.05 mg nitrite nitrogen (9). In this study the standard deviation of 12 identical samples was 1.6 percent for a nitrite nitrogen concentration of 1.9 mg/l.

Nitrate Nitrogen. Nitrate nitrogen is probably the most difficult of the nitrogen tests and was determined by the brucine method as described by Standard Methods (10, p. 461, 13th edition). Initially, sample clarification was attempted using activated carbon, but was later abandoned because the small sample used did not require clarification and also some nitrate was removed by adsorption on the carbon. Standard Methods (10, p. 464) lists a 15.4 percent standard deviation at 5 mg/l nitrate nitrogen. In this study the standard deviation of 12 identical samples was 10 percent for a nitrate nitrogen concentration of 7 mg/l.

pH. The pH of each sample was measured within about ten minutes of its withdrawal in order to minimize pH changes caused by the loss of dissolved carbon dioxide. A Beckman Model G portable battery powered pH meter equipped with a glass electrode was used to make field measurements. The normal range of accuracy of this procedure is about ± 0.1 pH unit (9).

Alkalinity. Sample alkalinity was determined by titration with sulfuric acid to an endpoint at pH 4.3 as measured by an on-line Beckman pH meter employing a glass electrode. A precision of ± 1 mg/l and an accuracy of ± 3 mg/l, expressed as $CaCO_3$, can be achieved in the range of 10 to 500 mg/l (9). Since normal pH levels were less than 8.3 the total alkalinity was composed almost entirely of bicarbonates.

Dissolved Oxygen. The Winkler azide modification of the iodometric method was used to determine dissolved oxygen concentration. The method was modified for the high dissolved oxygen concentrations used in this

study as described on page 413 of Standard Methods (9). For secondary effluents a standard deviation of about 0.06 mg/l is indicated (9).

Temperature. A mercury filled thermometer was used for this determination. The temperature was expressed to the nearest degree celsius.

Suspended Solids. Each sample was filtered through a 4.25 cm Whatman, grade GF/C, glass fiber filter pad for a suspended solids determination as described by Wycoff (11). A precision of 11.2 percent was reported for activated sludge effluent and 5 percent for mixed liquor analyses. These values included sampling and weighing errors. Blank pads were used for corrections in filter moisture content and fiber content.

Biochemical Oxygen Demand. Sample BOD was determined as described on page 415 of Standard Methods (9). Samples were treated with sulfuric acid to inhibit nitrifying organisms and then neutralized (12, p. 399). A pH of 2 was maintained for 30 minutes and then the samples were raised to pH 7 with sodium hydroxide. The dilution water was seeded with settled raw sewage. Seed corrections were computed from the blanks because of the small errors introduced compared to the overall test accuracy. When necessary, samples with high dissolved oxygen concentration were aerated to lower the oxygen content to air saturation. There is no standard against which the accuracy of the BOD test can be measured. The standard deviation of the results of 34 laboratories was 17 percent using a glucose-glutamic acid mixture. The precision obtained by a single analyst in his own laboratory was $\pm$ 5 percent (10).

Chemical Oxygen Demand. The COD of each sample was determined by the dichromate reflux method (9, p. 510). Silver sulfate was used as a catalyst and 0.4 grams of mercuric sulfate was used to complex the chlorides in the samples. The reported average standard deviation using reagent grade glucose is $\pm$ 8.2 percent. For most organic compounds 95 to 100 percent oxidation can be obtained based on the theoretical oxygen demand (9).

Rhodamine Dye Concentration. A Beckman DB spectrophotometer (550 mu) was used for this measurement for tracer studies. The use of a high concentration of this dye allowed visual observations of short-circuiting in the filter. It has been reported that a standard deviation of 1 to 2 percent is normal for absorbance measurements between 0.15 and 1.0 (13). This range of absorbance is the same as a transmittance range of 10 to 71 percent. In this study the standard deviation was about 2 to 5 percent for a transmittance range of 35 to 88 percent.

Analytical Errors. The systematic and analytical errors associated with the laboratory measurements were considered to be within the range of values published in Standard Methods (9 and 10). When non-standard but published analyses were used the variation was considered to be equal to that reported by the author of the test. Other systematic and analytical errors were calculated as necessary for this study. A summary of the variations which could be expected for the analyses is given in Table 5.

TABLE 5

SUMMARY OF ANALYTICAL ERRORS

Measuremnt	Method	Recovery	Precision	Reference
Organic Nitrogen	Kjeldahl Method	97.5-98.6%	± 0.03 mg/l	Standard Methods (9)
Ammonia Nitrogen	Direct Nesslerization	97-99%	± 0.001 mg ±2-5%	Standard Methods (9) This Study
Nitrite Nitrogen	Naphthylamine-hydrocnloride	-	Instrumental ± 0.05 mg	Standard Methods (9)
	Sulfanilic Acid		± 1.6%	This Study
Nitrate Nitrogen	Brucine Method	-	± 15.4%	Standard Methods (10) 13th Edition
			± 10	This Study
pH	Glass Electrode	-	± 0.1 pH Units	Standard Methods (9)
Alkalinity	H_2SO_4	-	± 1 mg/l	Standard Methods (9)
	Titration		± 1 mg/l	This Study
Dissolved Oxygen	Azide Winkler High DO	-	± 0.23 mg/l	Standard Methods (9)
Termperature	Hg-celsius Thermometer	-	± 1 °C	Standard Methods (9)
Suspended Solids	Glass Fiber Filter	-	± 11.2%	Wycoff (11)
Biochemical Oxygen Demand	BOD_5 at 20 °C	-	± 5%	Standard Methods (9) 13th Edition
Chemical Oxygen Demand	Dichromate + $HgSO_4$ + $AgSO_4$	95-100%	± 8.2%	Standard Methods (9)
Rhodamine Dye	Beckman DB Spectrophotometer	-	± 1-2% (10-71% Transmit.)	Skoog & West (13)
			± 2-5% (35-88% Transmit.)	This Study

SECTION VI

RESULTS OF FIELD STUDIES

This Section is divided into five parts. First a description is given of the characteristics of the Union Sanitary District wastewater effluent that was treated in the submerged filter pilot plant. The second and third parts present a summary of the data collected from both the preoxygenation filter with recycle and the bubble oxygenation filter. The fourth part contains data to illustrate how the two filters operated over a 24-hour period during which the waste characteristics varied considerably. Finally, a brief discussion of the characteristics of the various effluent nitrogen forms is given. Detailed data from operation of the filters is given in the Appendices.

Characteristics of the Influent Wastewater

The field submerged filter apparatus was operated at the Union Sanitary District Plant No. 3 located in Union City, California. During the period of the study the activated sludge process at this plant was operated at an average process loading of approximately 0.43 lbs of BOD_5 per lb of mixed liquor volatile solids (MLVS) with a range of 0.27 to 1.0. The measured quality of the effluent from the final settling tank is shown in Table 6. The lower typical concentrations of organic nitrogen, BOD, COD, suspended solids and grease prevailed at the beginning of the study and changed to the higher typical values during the latter half of the study. These values are representative of a great majority of the data, while the high and low values listed in other columns, represent extreme measurements. More detailed data can be found in Appendix A.

The characteristics of the effluent waste from the wastewater treatment plant was influenced by changes in the industrial waste contributory to it. Approximately 15 to 20 percent of the influent flow was from industrial sources. The principle contributing industries are producers of aluminum cans and sash, cast iron pipe, chain and detergents. Also, important industrial services include an industrial laundry and a meat packing plant. Potential operational problems can be associated with Al^{+++}, Fe^{++}, acids or alkalies, detergents and grease. The Al^{+++} and/or Fe^{++} were suggested as the cause of problems in the activated sludge process in August and September, during the middle and latter part of this study. Foaming tended to occur in any turbulent area following the activated sludge process (including the oxygenator of the preoxygenation filter).

Preoxygenation Filter With Recycle

The preoxygenation filter was started on May 4, 1971. After thirteen days of checking the system's mechanical operation, seed was added from one of the laboratory nitrifying filters. The field filter was operated at a 60 minute detention time. Between the 30th and 37th day there was

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TABLE 6

TYPICAL CHARACTERISTICS OF TREATED EFFLUENT FROM UNION SANITARY DISTRICT PLANT NO. 3

Parameter	Typical (mg/l)*	Low (mg/l)*	High (mg/l)*
NH_3-N	14-18	9	25
NO_2^--N	0.02-0.10	0.00	0.20
NO_3^--N	0.05-0.15	0.00	0.23
Org-N	4.0-8.0	1.8	8.8
DO	0.5-0.8	0.0	1.5
BOD	25-56	10	90
COD	100-150	75	235
Suspended Solids	20-69	10	140
Grease	2-12	-	-
pH (units)	7.3-7.6	6.7	7.9
Alkalinity (as $CaCO_3$)	320-350	200	470
Temperature (^oC)	20-25	16	31

* Units are mg/l unless otherwise specified.

a significant increase in efficiency of ammonia nitrogen removal (Figure 8). By the 66th day, 90 percent and greater ammonia nitrogen removal was obtained consistently. During this start-up period backwashing was performed twice per week at a rate of 6 to 20 gal/ft^2/min (usually 6 gal/ft^2/min). See Appendix B for a summary and Appendix C for detailed data at various detention times.

Filter Performance During Steady State Operation. In general the pre-oxygenation filter was operated with a total flow rate (influent wastewater plus recycle) through the filter varying from 0.82 to 1.29 gal/ft^2/min. The recycle ratio varied from 2.0 to 3.0.

Nitrogen Forms. Once an optimum degree of treatment was reached it remained fairly constant. The average percentage of ammonia nitrogen removal obtained at three different detention times is shown in Table 7. In the temperature range of 21 to 27 °C, 90 to 96 percent removal was obtained with a 60 minute detention time. The possible effect of temperature variations was overshadowed by variations in the suspended solids concentration and/or in the nitrifying bacteria population in the filter. As the detention time was increased from 30 to 60 minutes the removal efficiency became more consistent.

Typical concentrations of the different nitrogen forms in the filter influent and effluent are shown in Table 8. Errors in accuracy of the nitrogen balance between influent and effluent was most likely caused by errors in the nitrate test. At a detention time of 40 minutes the backwash rate was raised to 20 to 40 gal/ft^2/min. This apparently caused the nitrite nitrogen concentration in the filter effluent to rise. The Nitrobacter population seemed to be more hindered by backwashing than the Nitrosomonas population.

After the percent removal of ammonia nitrogen was established at a 60 minute detention time, a study was undertaken to observe how the various nitrogen forms changed with depth in the filter (Figure 9). A more detailed view of the ammonia nitrogen, nitrite nitrogen, and dissolved oxygen changes with depth is shown in Figure 10. Because of the high recycle ratio and low ammonia nitrogen in the activated sludge plant effluent, the influent ammonia nitrogen concentration (2.84 mg/l) to the filter was quite low. Some suspended organic nitrogen removal occurred as suspended solids were removed in the bottom (influent end) of the filter. The dissolved oxygen consumption paralleled the ammonia nitrogen removal well (Figure 10). There was an immediate ammonia nitrogen oxidation at the influent end of the filter where NH_3-N concentration was highest, as predicted by kinetic considerations. The decrease in the rate of ammonia oxidation with height in the filter results from the decreasing substrate concentration and the particular way in which the filter was packed with biological solids. In the bottom half of the filter the rate of nitrite oxidation was equal to the rate of ammonia oxidation. In the top half of the filter the rate of ammonium nitrogen oxidation fell below the rate of nitrite nitrogen oxidation.

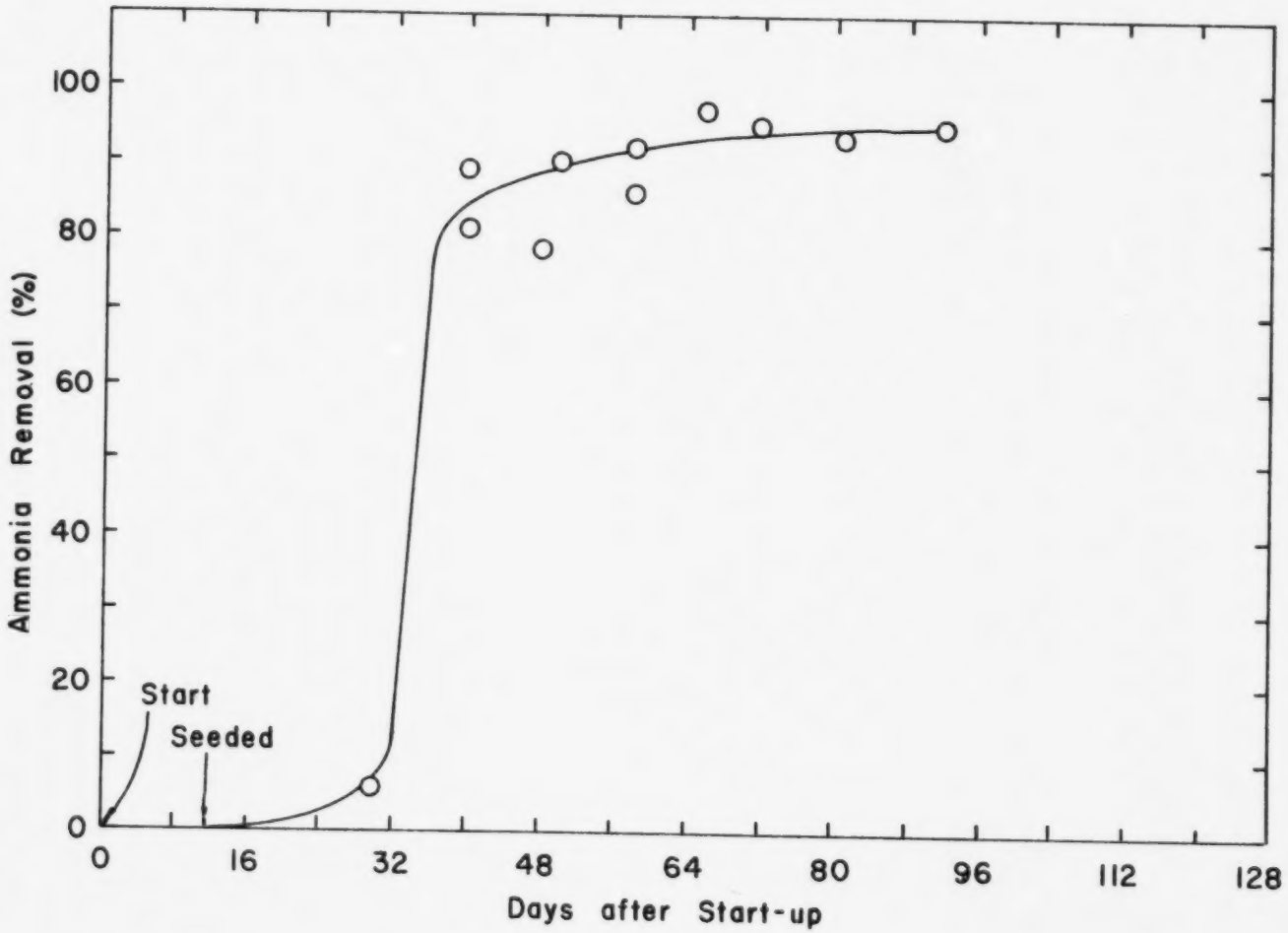

Figure 8. Percent ammonia removal versus time during filter start-up (preoxygenation with recycle - 60 minute detention time).

TABLE 7

AMMONIA NITROGEN REMOVAL IN THE PREOXYGENATION FILTER

Detention Time(min)(1)	Recycle Ratio (2)	Number of Days Operation	Number of Samples	Influent NH_3-N(mg/1)	Effluent NH_3-N(mg/1)	Percent Removal
60	2.75	40	8	14.3 ±2.6	1.0 ±0.4	93 ±3.1
40	3.0	27	10	19.6 ±4.2	5.6 ±2.6	71 ±10.8
30	2.0 & 3.0	62	18	15.2 ±3.6	6.9 ±3.1	55 ±15.7

TABLE 8

TYPICAL INFLUENT AND EFFLUENT NITROGEN CONCENTRATIONS IN THE PREOXYGENATION FILTER

Detention Time(min)(1)	Organic-N(mg/1)		NH_3-N(mg/1)		NO_2^--N(mg/1		NO_3^--N(mg/1)		Total-N (mg/1)	
	Influent	Effluent	Influent	Effluent	Influent	Effluent	Influent	Effluent	Influent	Effluent
60	3.6	1.5	14.3	1.0	0.05	0.6	0.1	15.9	18.0	19.0
40	-	-	19.6	5.6	0.05	4.1	-	6.9	-	-
30	5.7	2.5	15.2	6.9	0.04	1.7	0.1	6.0	21.0	17.1

(1) Based on the filter void volume and the raw wastewater flow rate.
(2) Recycle Ratio = recycle flow rate/wastewater flow rate.

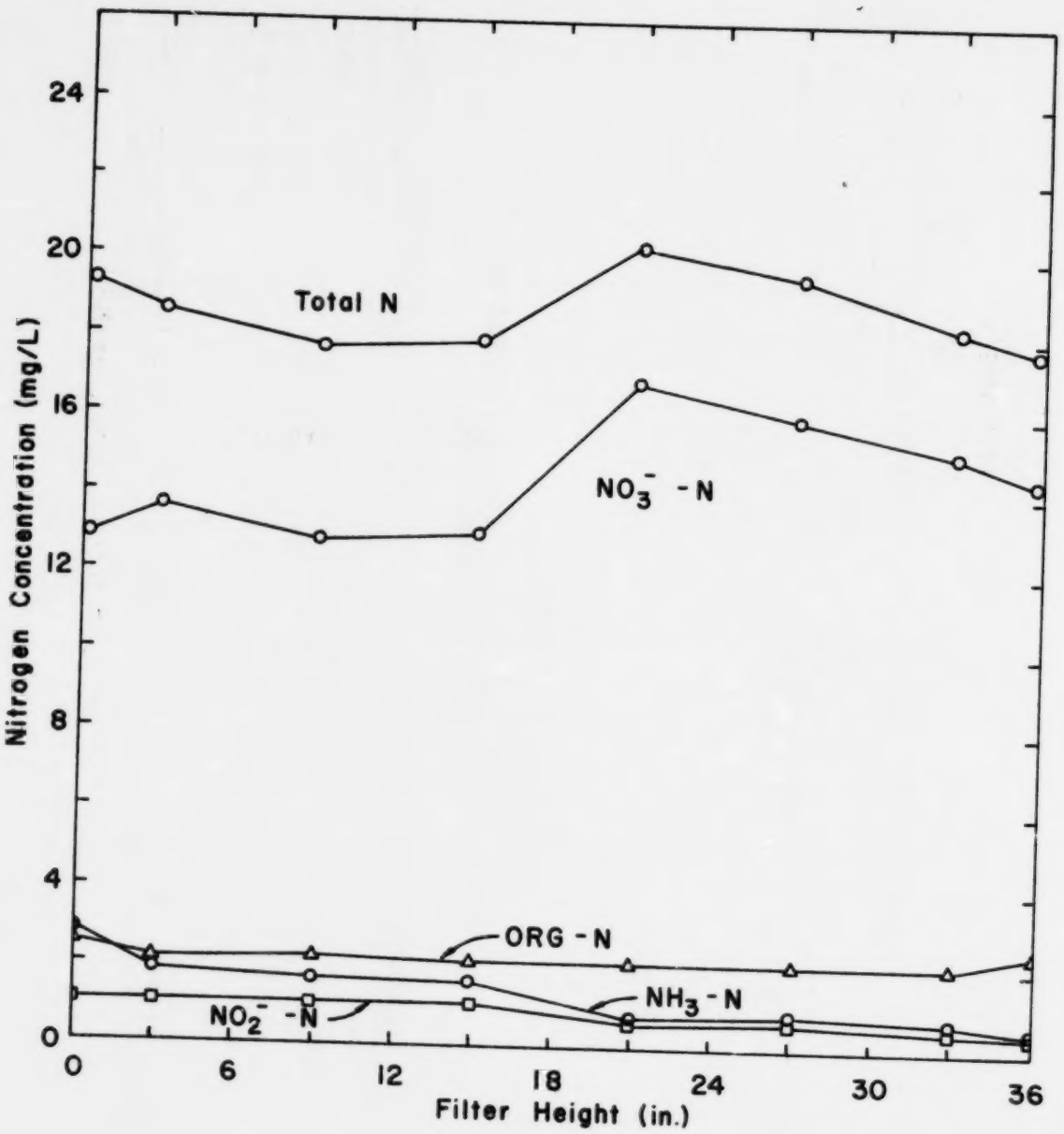

Figure 9. Nitrogen profile through filter (preoxygenation with recycle of 2.75; 60 minute detention time; influent NH_3-N conc. of 10.6 mg/1).

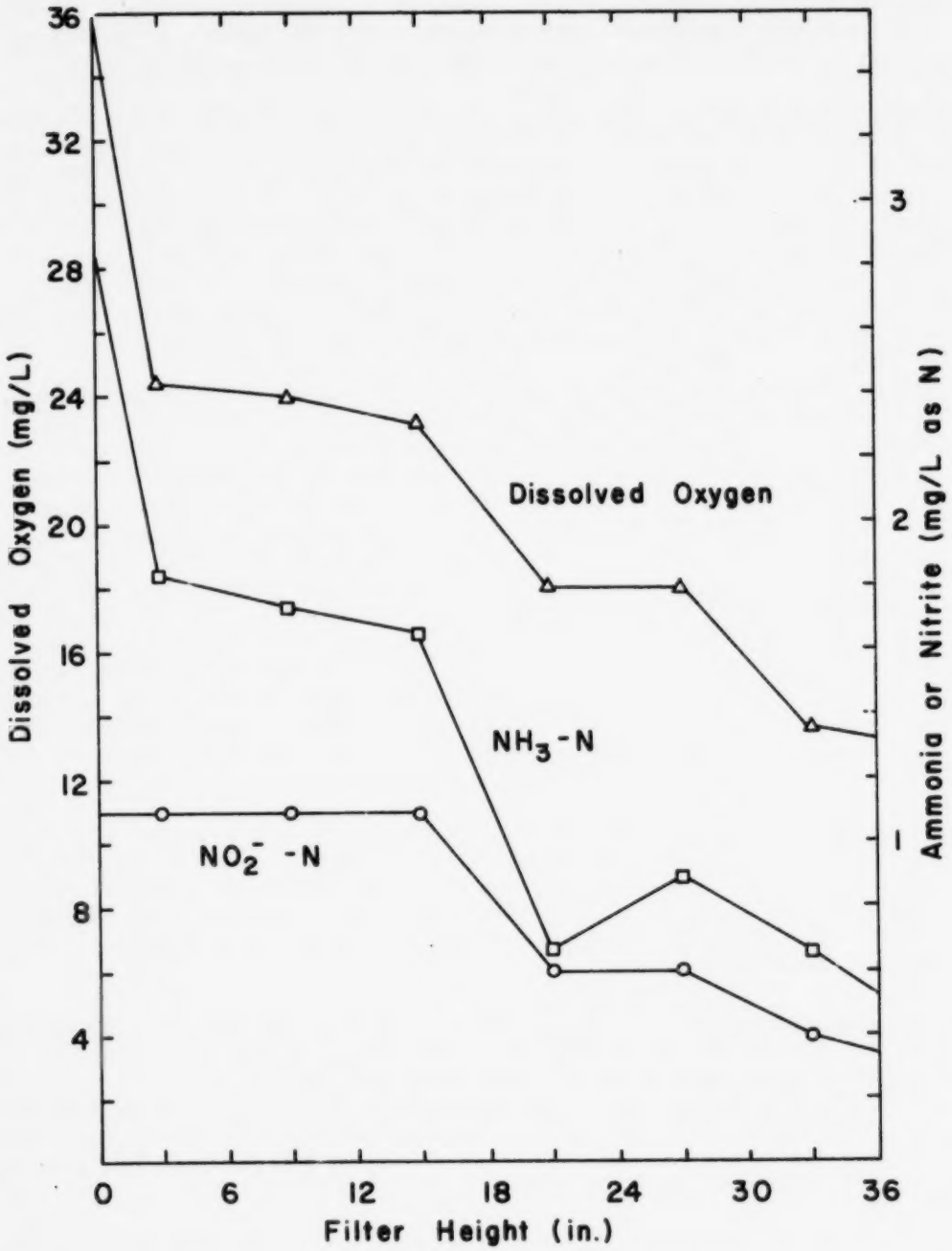

Figure 10. Profile of dissolved oxygen, ammonia, and nitrite in the preoxygenation filter (60 minute detention time).

It should be noted that the standard deviation of the total nitrogen balance for this specific test was ± 5 percent. Considering the precision of each of the nitrogen tests a 10 to 15 percent error in the total nitrogen balance is easily possible. Loss of nitrogen by denitrification or suspended solids removal did not appear significant, at least within the analytical error of nitrogen analysis.

BOD, COD and Suspended Solids. The reductions in BOD, COD and suspended solids through the filter are listed in Tables 9, 10, and 11, respectively. The 60 minute detention time resulted in a 76 to 96 percent reduction in BOD; a 45 to 57 percent reduction in COD; and an 81 to 93 percent reduction in suspended solids. Change in detention time did not affect percent BOD reduction as greatly as it did the ammonia nitrogen removal. The suspended solids were removed quite well, apparently due to the quiescent conditions in the filter. Most likely straining and adhesion were important mechanisms of solids removal.

Oxygenation. The oxygenator routinely attained 60 to 87 percent oxygen saturation in the wastewater with oxygen transfer efficiencies varying from 1.2 to 4.0 percent. This transfer calculation was based on the difference in the dissolved oxygen between the oxygenator influent (influent waste plus recycled effluent) and the oxygenator effluent. The oxygenator influent, DO_i, was calculated from the measured influent untreated wastewater dissolved oxygen concentration, DO_w, and the measured filter effluent dissolved oxygen concentration, DO_e. The oxygenator effluent (equivalent to the dissolved oxygen of the filter influent) was measured routinely. The efficiency was calculated by multiplying 100 times the ratio of the total pounds of oxygen transferred per day by the oxygenator to the total pounds of oxygen drawn out of a cylinder per day. This low transfer efficiency was due to the oxygenator design and operation. Much higher transfer efficiencies could, without a doubt, be obtained if designed for this purpose.

pH and Alkalinity. The influent always had a high alkalinity and the pH through the filter typically varied between 7.4 and 7.1. The ratio of change in alkalinity to change in ammonia nitrogen concentration is theoretically 7.13 and during this study the measured ratio averaged 8.0 at a 60 minute detention time and approximately 6.7 at a 30 and 40 minute detention time.

Clogging and Short-circuiting. The filter was operated at a 60 minute detention time for three and one-half months and was backwashed at 6 to 20 gal/ft^2/min twice a week. The lower backwashing rate was used most of the time. During the third month a dye study was performed to determine the extent of clogging and short-circuiting. At this time the recycle ratio was 2.62 to 1 so that the single pass detention time in the filter itself was 16.6 minutes.

Rhodamine dye was injected as a 15 second pulse into the influent line of the filter on two separate occasions, once just before backwashing

TABLE 9

BOD REMOVAL IN THE PREOXYGENATION FILTER[1]

Detention Time(min)[2]	Number of Samples	Influent BOD(mg/l)	Effluent BOD(mg/l)	Percent Removal BOD
60	4	35 ±6	5 ±3	86 ±10
40	2	38	3.4	91
30	3	37	9.6	74

TABLE 10

COD REMOVAL IN THE PREOXYGENATION FILTER[1]

Detention Time(min)[2]	Number of Samples	Influent COD(mg/l)	Effluent COD(mg/l)	Percent Removal BOD
60	4	104 ±15	51 ±12	51 ±6
40	2	113	61	46
30	4	124	54	56

TABLE 11

SUSPENDED SOLIDS REMOVAL IN THE PREOXYGENATION FILTER[1]

Detention Time(min)[2]	Number of Samples	Influent S.S.(mg/l)	Effluent S.S.(mg/l)	Percent Removal S.S.
60	4	27 ±3	3.5 ±4	87 ±6
40	3	38	6.6	83
30	6	25 ±5	6.5 ±3	74 ±4

(1) No standard deviation was calculated on data based on less than four samples.

(2) Based on raw wastewater flow rate and filter void volume.

(2 days after the previous backwash) and once just after backwashing (Figure 11). The single pass theoretical detention time in the filter including entrance and exit volumes was 20.8 minutes for this dye study. As can be seen, there was less short-circuiting in the filter after backwashing due to less suspended solids in the filter. The dye could be visually observed running up the sides of the filter. In the before-backwash test it appeared that about 1/4 of the dye had reached the filter exit after 6 minutes of elapsed time. For the same amount of dye the time elapsed in the after-backwash test was 9 minutes. The mean detention times for the before-backwash and the after-backwash tests were 10 and 14 minutes, respectively.

The filter had a column to rock diameter ratio of 5.5 to 1, which was not large enough to completely eliminate wall effects and short-circuiting even though wall dispersion rings were provided. This short-circuiting could be especially significant at short detention times. In Table 7 it was reported that a 55 percent ammonia nitrogen removal was obtained at a 30 minute detention time. There was one 3 week period during which the ammonia nitrogen removal at this detention time averaged 71 percent, but later it decreased. It is possible that the suspended solids in the filter were arranged to give less short-circuiting during this particular period of time. Thus it is possible that slightly better efficiencies could be obtained with a filter with a larger column diameter.

Rate of Suspended Solids Accumulation in the Filter. The rate at which suspended solids accumulate within the filter is an important engineering consideration. Solids accumulation can lead to clogging. Further, in order to prevent clogging, the suspended solids will have to be removed periodically for subsequent disposal. An estimate of the quantity which will be removed is important for the design of the disposal facilities.

Suspended solids accumulation will result from various factors. First, some accumulation will result from suspended solids in the influent which are removed within the filter. Some of that removed will be oxidized by biological action within the filter so that the accumulation from this source should be something less than the quantity of influent solids removed. Second, some biological suspended solids will be produced within the filter from utilization of soluble wastewater organics by microorganisms within the filter (0.1 to 0.4 mg produced per mg soluble COD removed, depending upon the detention time of the cells within the filter). Finally, some biological suspended solids will result from nitrogen oxidation (0.1 to 0.3 mg per mg NH_3-N oxidized, also depending upon the retention time of organisms in the filter). Estimates of anticipated suspended solids accumulation could be made on this basis, but it was desired to make some measurements in order to see if firmer figures could be obtained. This proved to be a difficult task because of varying wastewater characteristics and the inability to directly measure the suspended solids concentration within the filter.

Three approaches were used in an attempt to quantify the rate of accmulation of suspended solids in the preoxygenation filter. They involved a suspended solids balance; a COD, nitrogen and oxygen balance; and last,

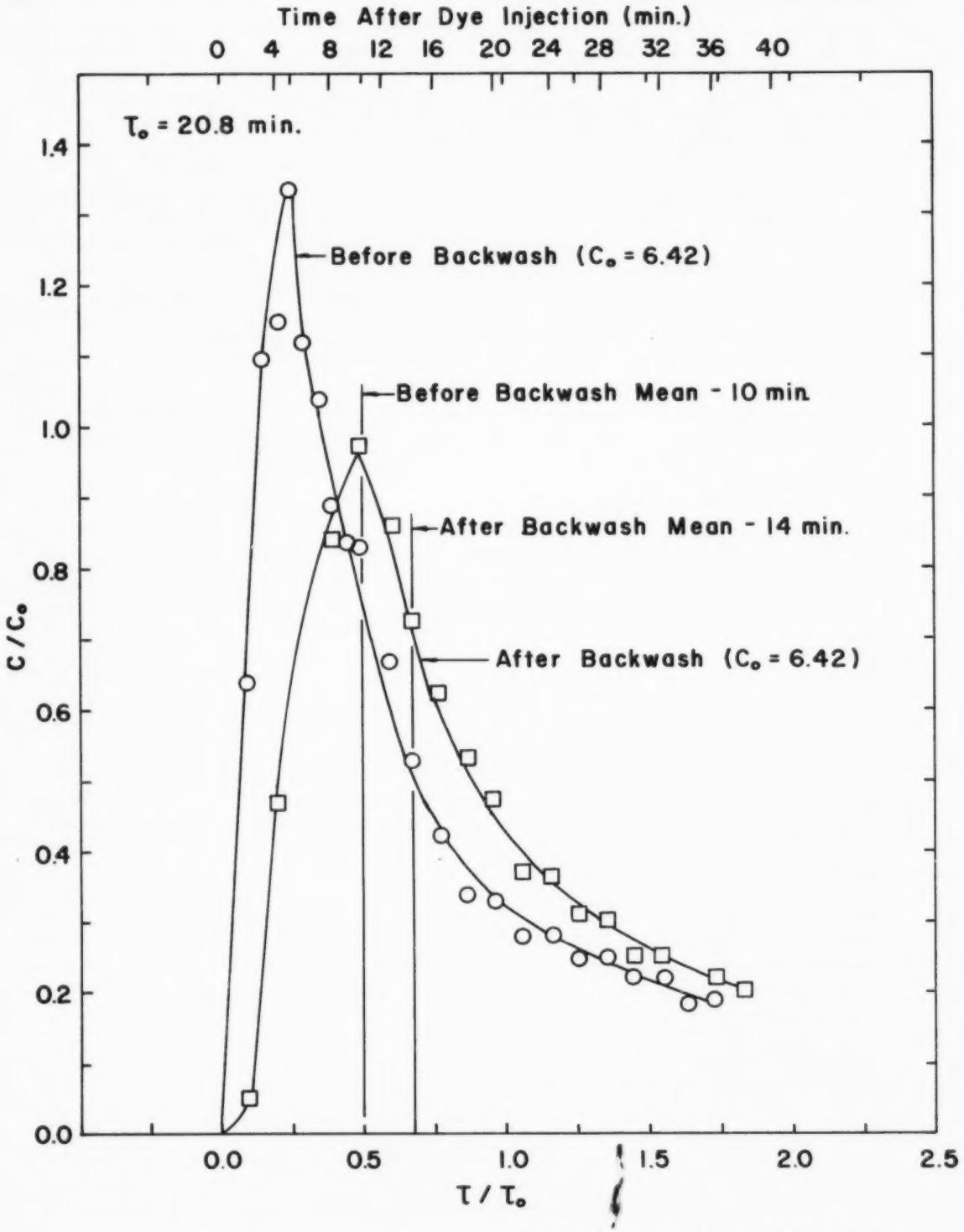
Time After Dye Injection (min.)
0 4 8 12 16 20 24 28 32 36 40
T_o = 20.8 min.
Before Backwash (C_o = 6.42)
Before Backwash Mean - 10 min.
After Backwash Mean - 14 min.
After Backwash (C_o = 6.42)
C / C_o
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4
0.0 0.5 1.0 1.5 2.0 2.5
T / T_o

Figure 11. Rhodamine dye tracer study of the preoxgenation filter.

an approach which considered suspended solids removal and oxidation, and suspended solids production due to both nitrification and the oxidation of organic matter. During the start-up period many of the influent suspended solids will be removed and will remain in the filter for a long period of time. Later, after reasonably steady-state conditions develop, the rate at which suspended solids are leaving the filter should equal the rate at which they are accumulating.

The first approach was to make a simple balance based upon the difference between suspended solids entering and leaving the filter (Table 12). The suspended solids accumulation was assumed to be equal to the difference between the influent and effluent suspended solids. The solids removed during backwashing were collected every 2 to 4 days for a total of 10 times during a 29-day period of operation. The average quantity of suspended solids removed by backwashing was 1.4 grams/day. This represents 31 percent of the 4.7 grams/day removed during waste passage through the filter. Thus solids were either increasing in concentration in the filter or else they were being oxidized. The former was at least partially the reason because the filter became clogged with suspended solids within 3 weeks after this data was collected.

The above approach ignored all the suspended solids removing, oxidizing and forming reactions taking place within the filter. A second approach was tried that takes these processes into consideration. It was based on a COD, nitrogen and oxygen balance. The COD of 1 mg/l of biological suspended solids commonly has been found to be approximately 1.4 mg/l. Most of the COD removal (60 to 70 percent) was due to the suspended solids removal in the filter. The actual oxygen used in the filter was consumed by both nitrification and the oxidation of organic matter (COD). If the oxygen demand of the oxidized ammonia nitrogen is subtracted from the total oxygen used within the filter, the difference equals the quantity of COD oxidized. The quantity of COD oxidized was very low considering the amount of COD removed (Table 13, Column H). This is in part due to the low dissolved oxygen concentration within the bacterial solids in the filter. More discussion on the degree of carbonaceous oxidation appears in the next section in relation to the total oxygen demand in the filter.

It was assumed that total COD removal minus the COD oxidized is a measure of suspended solids accumulation. By dividing the unoxidized but removed COD by 1.4 mg COD/mg S.S. the actual suspended solids accumulation in the filter could be calculated. Where COD data was available the above calculations were performed at the various detention times. Note that the influent COD analyses were somewhat high because of excess suspended solids collection in the influent sample, therefore, this error was subtracted from the above calculations (Table 13). This error was monitored by comparing the data from the influent samples from the project and the data from the effluent sampler at the Union Sanitary District Plant No. 3. The overall suspended solids accumulation rate was 27 ± 9.5 mg/l (based on the influent wastewater flow rate). Theoretically this was a logical approach but the small amount of COD data and

TABLE 12

SUSPENDED SOLIDS BALANCE IN THE PREOXYGENATION FILTER
(30 minute detention time)

	Days After Start-up	Suspended Solids-mg/l			Estimated S. S. Accumulated		Wasted S. S. During Back-washing (g/d)	Percentage Removed by Backwashing
		Influent	Effluent	Differences	g/day	g/liter-day		
Average or Range:	95-125	27	9(1)	18	4.7	0.86	1.4	31
Number of Samples:	-	28	3	-	-	-	10	-
Standard Deviation:	-	±7.6	-	-	±2.0	-	-	-

(1) Average from three samples; assumed to be constant.

TABLE 13

SUSPENDED SOLIDS ACCUMULATION IN THE PREOXYGENATION FILTER
BASED ON A COD, NITROGEN AND OXYGEN BALANCE

Number of Samples	Detention Time(min)	Days After Start-up	Total DO Used mg/l	Calculated Oxygen Demand from Nitrification mg/l	Total COD Removed mg/l(2)	Total COD Oxidized mg/l	Estimated S. S. Accumulation (Based on Influent Wastewater Flow) (1)		
							mg/l	g/day	g/liter-day(3)
(A)	(B)	(C)	(D)	(E)	(F)	(G)		(H)	
4	60	57-70	75.2	64.9	53.5	10.3	31 ±12.1	4.1	0.75
1	40	183	56.8	43.4	53.4	13.4	29	5.7	1.0
4	30	105-125	61.6	45.3	48.6	16.3	23 ±6.6	6.0	1.1

(1) Suspended Solids Accumulation $= \dfrac{\text{COD Removed} - [\text{DO Used} - (4.57(NH_4^+\text{-N oxidized}) - 1.14\ (NO_2\text{-N})_{Eff.})]}{1.4 \text{ mg COD/mg S. S.}}$

(2) The suspended solids error was subtracted from the influent COD; the source of the error was the influent composite sampler (checked with Union Sanitary District sampler).

COD Oxid(corrected) = COD Oxid(actual data) - (excess S.S.)(1.4 mg COD/mg S.S.)

(3) In filter void volume.

the fairly high standard deviation reduced its accuracy. However, the accumulation in the filter in grams/day was surprisingly close when comparing the different methods used in Tables 14 and 15.

The Third approach to finding the suspended solids accumulation rate was to directly consider influent suspended solids which are removed by the filter plus an estimate of suspended solids produced from nitrification and soluble COD oxidation (Table 14). Then loss of suspended solids within the filter through oxidation is estimated as it was in Column G of Table 13. The first sources of suspended solids are the actual influent suspended solids removed by the filter. This can be determined as by the first approach. The second and third sources of suspended solids are the organisms produced during the removal of soluble COD and during nitrification. The effluent suspended solids data are all average values, but are fairly representative. The most inaccurate data is the change in soluble COD and concentration of COD oxidized. In many cases these data were simply estimated, but the relative influence of these changes was small compared with the suspended solids contributing factors.

The influent suspended solids concentration was high during some months of filter operation (Table 14). Therefore, the suspended solids accumulation rate was also high. This resulted in a low percentage of nitrifying bacteria in the suspended solids within the filter. This is in marked contrast to the situation in the laboratory study where there was no influent suspended solids and the suspended solids within the filter consisted mainly of nitrifying bacteria. Because of the much lower estimated percentage of nitrifying bacteria within the filter in the field study, the efficiency of nitrification under comparable conditions of detention time and influent ammonia nitrogen concentration should be much lower than obtained in the laboratory. This would appear to be a very important parameter in explaining the results obtained.

All three of the approaches used to estimate suspended solids accumulation within the filter have sources of error. However, there is a general consistency between the estimates by the three different methods. The data contained in Table 14 suggest that suspended solids accumulation from dissolved COD removal and nitrification (columns G and I) is a smaller but still significant portion of the suspended solids accumulation when compared with accumulation from suspended solids in the influent (column D). The third method described (Table 14) is perhaps the best to use in estimating suspended solid accumulations in filters.

Oxygen Requirements for Carbonaceous Oxidation. As already suggested some oxygen was required for oxidation of organic matter entering the filter as well as for nitrification. A correlation between BOD_5 removal by the filter and oxygen demand above that required for nitrification is shown in Table 15. Much of the influent BOD_5 was in the form of suspended solids. The oxygen consumed by the oxidation of organic matter

TABLE 14

SUSPENDED SOLIDS (S.S.) ACCUMULATION BASED ON TRAPPED S.S. AND S.S. PRODUCTION DUE TO NITRIFICATION AND THE OXIDATION OF ORGANIC MATTER

Detention Time (min)	Month	Days After Start-up	Average Monthly Inf. S. S. Minus Eff. S.S. (mg/l)(1)	COD (mg/l)			Nitrification (mg/l)		Total S. S. Accumulation		Percent Nitrifying Bacterial Solids (6)
				Soluble Reduction	Oxidation	Resulting S.S. Production (3)	NH_4^+-N Oxidized	Resulting S.S. Production (4)	(mg/l) (5)	g/liter-day	
(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)	(I)	(J)		(K)
60	June	28-57	18	20(2)	10	7	14.3	2.5	28	0.67	9
60	July	58-88	17	20(2)	10	7	14.8	2.6	27	0.65	10
60	Jan.	243-274	59	35(2)	10	18	18.7	3.3	80	1.9	4
40	Mid-Oct. to Mid-Nov.	164-191	45	20	13	5	12.8	2.2	52	1.9	4
30	Aug.	80-110	25	26	16	7	7.3	1.3	33	1.6	4
30	Sept.	111-140	20	26	16	7	8.1	1.4	28	1.3	5
30	Dec.	212-233	46	34(2)	16	13	5.0	0.9	60	2.9	1.5

(1) Influent data from Appendix A; effluent data assumed to be 5 mg/l at 40 and 60 minute detention time; and 9 mg/l at a 30 minute detention time.

(2) Estimated from influent S. S. and BOD data.

(3) (E-F)/1.42.

(4) 0.15 X (NH_4^+-N oxidized).

(5) J = D + G + I.

(6) K = I X 100/J.

TABLE 15

CORRELATION BETWEEN CARBONACEOUS OXYGEN DEMAND AND BOD_5 REMOVAL

Detention Time(min)	Days After Start-up	Number of Samples	ΔO_2 (1) mg/l	ΔBOD_5 (2) mg/l	$\frac{\Delta O_2}{\Delta BOD_5}$
(A)	(B)	(C)	(D)	(E)	(F)
60	48-90	6	26 ±11	34 ±6	0.78 ±0.28
40	164-191	3	14	42	0.34 ±0.12
30	98-218	10	20 ±10	32 ±6	0.62 ±0.28
Overall	-	-	-	-	0.63 ±0.28

(1) Oxygen consumed to oxidize organic matter =
Total O_2 Used - $[4.57(NH_4^+\text{-N oxidized}) - 1.14(NO_2^-\text{-N})]$.

(2) Influent BOD_5 - Effluent BOD_5.

was obtained by subtracting the calculated nitrification oxygen demand from the total oxygen consumed within the filter. Somewhat surprisingly, the carbonaceous oxygen demand within the filter was less than the BOD_5 removed. The ratio of these two quantities averaged 0.63 $\pm$ 0.28 at all detention times. At a 60 minute detention time this fraction was 0.78 $\pm$ 0.28. Thus it appears that when suspended solids are detained within the filter for periods of 10 to 25 days they are not as completely oxidized as when they are held in a more diluted form in a BOD bottle for only five days.

Effects of Anaerobic and Idle Aerobic Conditions. The preoxygenation filter rarely became completely devoid of oxygen because the turbine blades in the oxygenator always ran and thus always supplied some aeration even during times when pure oxygen was not flowing into the oxygenator. During periods when insufficient dissolved oxygen was supplied, nitrification decreased to negligible values while the oxidation of carbonaceous BOD consumed the available oxygen. At times of insufficient dissolved oxygen a few black areas developed within the filter. It is difficult to make any quantitative statements about filter recovery after such periods. One episode is illustrated by Figure 12. During the first 20 days shown the filter was operated at a 30 minute detention time. Unknown problems (perhaps high influent suspended solids or toxicity) arose and the efficiency of ammonia nitrogen removal decreased.

On the 22nd day the filter was changed to operate at a 60 minute detention time and samples were collected during the next 14 days. On about the 32nd or 33rd day the filter oxygen supply failed and the filter became partially anaerobic for 1 or 2 days. Recovery appeared rapid after the oxygen supply was restored. Similar partially anaerobic conditions occurred at other times early in the study and the filter never seemed to be seriously affected for any prolonged length of time.

A planned study to determine the effect of four days without feed (under aerobic conditions with recycle and oxygenation) was started on day 51 (Figure 12). This four day idle period had little effect on the efficiency of ammonia nitrogen removal after 24 hours of operation. Point E (Figure 12) represents a composite sample collected during the 24 hour period after the influent feed was started. Point F represents a grab sample collected at the end of the above 24 hour period. It appears that the filter recovered immediately. It must be noted that during the 35th to the 70th day the influent suspended solids and BOD_5 were extremely high. Thus the expected maximum ammonia nitrogen removal efficiency was only 70 to 85 percent (not 93 percent as under more favorable conditions). Short anaerobic periods or periods without waste addition do not appear to seriously hamper the operation of the preoxygenation filters.

Bubble Oxygenation Filter

Filter Start-up and Seeding. This filter was started on August 11, 1971. After a 5-day initiation period, a refrigerated nitrification seed was

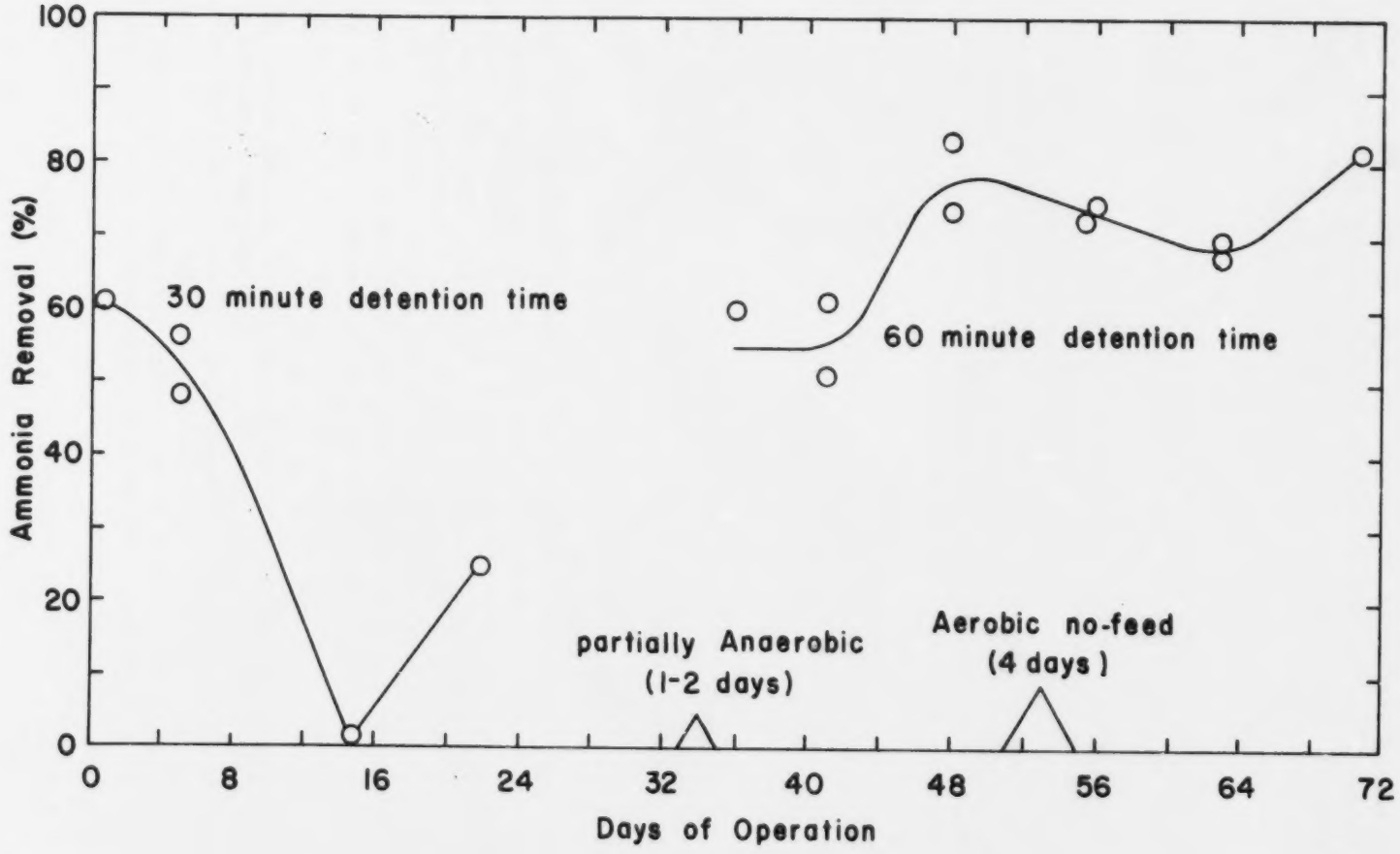

Figure 12. Recovery of Preoxygenation Filter from anaerobic and idle aerobic conditions.

added to the filter. The filter was initially operated at a 60 minute detention time. Between the 21st and 30th day of operation there was a large increase in efficiency of ammonia nitrogen removal (Figure 13). By the 70th day about 90 percent removal was maintained consistently. During this start-up period very little backwashing was required since most of the excess solids were carried out with the effluent from the filter. See Appendix B for a data summary and Appendix C for detailed data for different detention times.

Filter Performance During Steady-State Operation. In general the influent flow rate to the filter varied between 0.22 to 0.44 gal/ft^2/min.

Nitrogen Forms. After steady-state conditions developed, data was collected to ascertain ammonia nitrogen removal at a 60 minute detention time (Table 16). A 87 to 95 percent removal was attained with temperature varying between 16 and 30 ^{o}C. Some effect of temperature on efficiency was evident during the start-up phase of operation. However, as the suspended solids concentration increased within the filter, temperature effects were no longer easily distinguishable.

Typical nitrogen influent and effluent data is depected in Table 17 for a 60 minute detention time. The rising bubbles of oxygen in the filter tended to maintain a state of turbulence. This turbulence caused a variable and relatively high concentration of suspended solids to be present in the effluent.

Samples were collected at a 30 minute detention time but the data was not meaningful when compared to the data in Table 16. The efficiency of ammonia nitrogen removal varied between 0-59 percent (Appendix C). The data was not representative of normal operation because of high influent suspended solids and many operational problems.

Samples were collected at various filter heights to determine the reactor hydraulics and ammonia nitrogen removal characteristics (Figure 14). Less than one-half of the influent ammonia nitrogen remained in the sample taken 3 inches from the filter bottom. The alkalinity and ammonia nitrogen concentration decreased together while the dissolved oxygen concentration increase resulted from the continuous oxygen transfer during the rise of the oxygen bubbles throughout the height of the filter. The profile concentration in the field unit were very similar to those of the laboratory filter.

BOD, COD and Suspended Solids. The suspended solids wasting aspect of this filter caused lower percent removals of BOD, COD, and suspended solids than obtained with the preoxygenation filter. At a 60 minute detention time there was a 67 to 81 percent BOD removal; from 41 to 59 percent COD removal; and from 8 to 88 percent suspended solids removal (Table 18). At a detention time of 30 minutes removal of these constituents was lower.

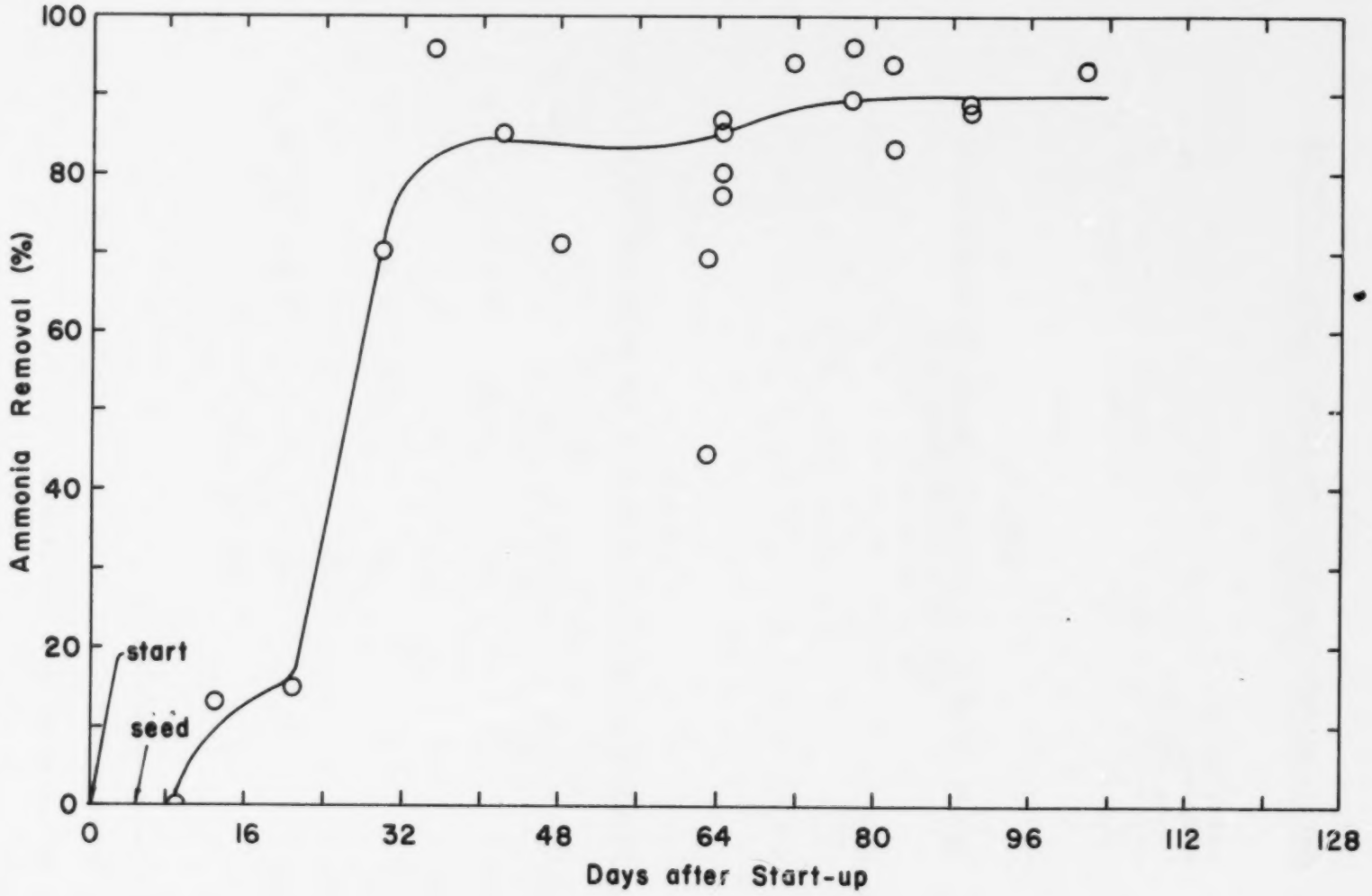

Figure 13. Percent ammonia removal versus time during start-up (Bubble oxygenation system - 60 minute detention time).

TABLE 16

AMMONIA NITROGEN REMOVAL IN THE BUBBLE OXYGENATION FILTER
(60 minute detention time) (1)

Number of Days of Operation (these samples)	Number of Samples	Influent NH_3-N(mg/1)	Effluent NH_3-N(mg/1)	Percent Removal NH_3-N
33	8	18.3 ±4.2	1.8 ±1.0	91 ±4.2

TABLE 17

TYPICAL INFLUENT AND EFFLUENT NITROGEN CONCENTRATIONS IN THE BUBBLE OXYGENATION FILTER
(60 minute detention time) (1)

Organic-N(mg/1)		NH_3-N(mg/1)		NO_2^--N(mg/1)		NO_3^--N(mg/1)		Total-N(mg/1)	
Inf.	Eff.	Inf.	Eff.	Inf.	Eff.	Inf.	Eff.	Inf.	Eff.
5(2)	2.2-4.7	18.3	1.8	0.0	0.4	0.0	18.3	23.3(2)	23.9(2)

TABLE 18

BOD, COD AND SUSPENDED SOLIDS REMOVAL IN THE BUBBLE OXYGENATION FILTER

Parameter	Number of Samples	Detention Time(min)(1)	Influent (mg/1)	Effluent (mg/1)	Percent Removal
BOD	5	60	37 ±3	9.5 ±3	74 ±7
BOD	2	30	43	25	41
COD	5	60	127 ±18	63 ±18	50 ±9
COD	2	30	137	80	42
S.S.	6	60	30 ±10	16 ±14	48 ±40
	2	30	48	51	-

(1) Based on filter void volume and untreated waste flow rate.

(2) Estimated due to a lack of data.

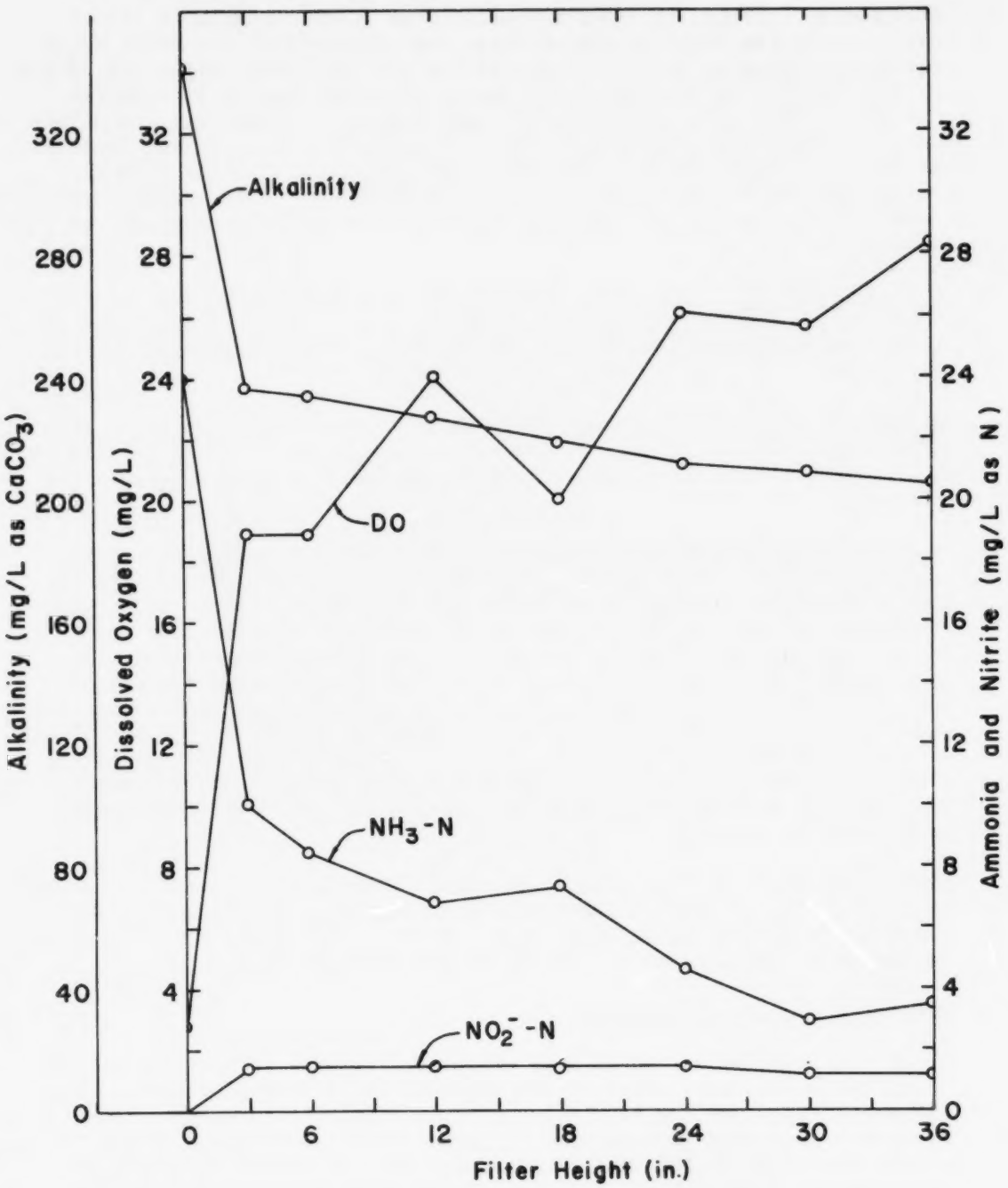

Figure 14. Profile of DO, alkalinity, NH_4^+-N, and NO_2^--N concentrations in the bubble oxygenation filter (60 minute detention time).

Oxygenation. The oxygen transfer efficiency ranged from 1.5 to 5.0 percent. This calculation was based on the amount of oxygen theoretically required to oxidize the organic matter (BOD), ammonia nitrogen and nitrite nitrogen, and the effluent dissolved oxygen concentration. The efficiency of oxygen transfer was calculated by multiplying 100 times the ratio of the total oxygen used per day (theoretical for known NH_4^+-N and carbonaceous oxidation) in the filter and the total oxygen discharged in the effluent of the filter per day to the total oxygen bubbled into the filter from the pure oxygen cylinder per day. These very low oxygen transfer rates were caused by a short distance of bubble travel (approximately 40 inches), large bubble size, and most important the lack of a recycle system for the oxygen. Future pilot plants should employ oxygen recycling so that oxygen transfer under more realistic conditions can be evaluated.

pH and Alkalinity. The ratio of decrease in alkalinity to the NH_3-N oxidized was 7.8 for a 60 minute detention time. This was about the same as for the preoxygenation filter. Also, the pH changes were of the same magnitude.

Clogging and Short-circuiting. This filter never clogged during a five-month period of operation. It was partially drained (6 to 20 gal/ft^2/min) once a week to prevent suspended solids accumulation in the base of the filter.

Anaerobic and Idle Aerobic Conditions. The bubble oxygenation filter accidently went without oxygen twice in a period of two months (Figure 15). The filter biological solids became very black during the second anaerobic period. The period needed for recovery in both cases was about three weeks. This was longer than the recovery period for the preoxygenation filter. A possible reason for the long recovery period was the loosening of attached organisms from the rock surface during the anaerobic period and subsequent removal from the filter by the turbulence of rising bubbles and the flowing waste. It should be noted that during this time period the influent suspended solids and BOD were extremely high so that expected maximum ammonia nitrogen removal efficiency was only 40 to 50 percent.

There were also two idle aerobic periods. Both showed a complete recovery within 24 hours. Point E represents a 24 composite starting immediately after the start of the influent feed. Point F represents a grab sample collected 24 hours after restarting of the influent feed.

Diurnal Variation in Operation

On two separate occasions 24 hour composite and grab samples (collected every two hours) were taken of the influent and effluent to the preoxygenation filter and the bubble oxygenation filter (Figure 16). This study was conducted to determine how each filter would react to the normal variation in influent ammonia nitrogen concentration over a 24 hour period. The high effluent ammonia nitrogen concentration at the

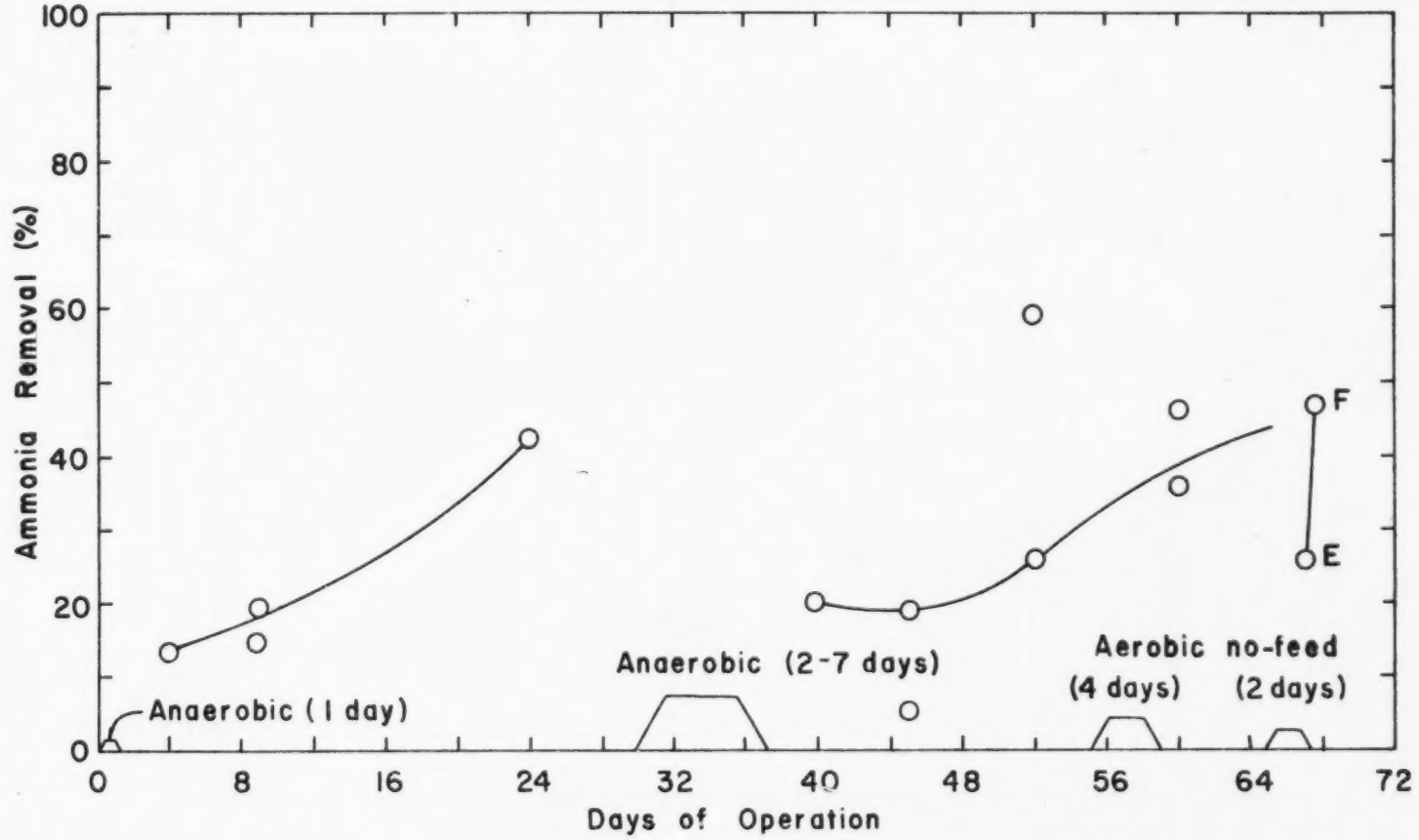

Figure 15. Recovery of Bubble Oxygenation Filter from anaerobic and no feed conditions (30 minute detention time).

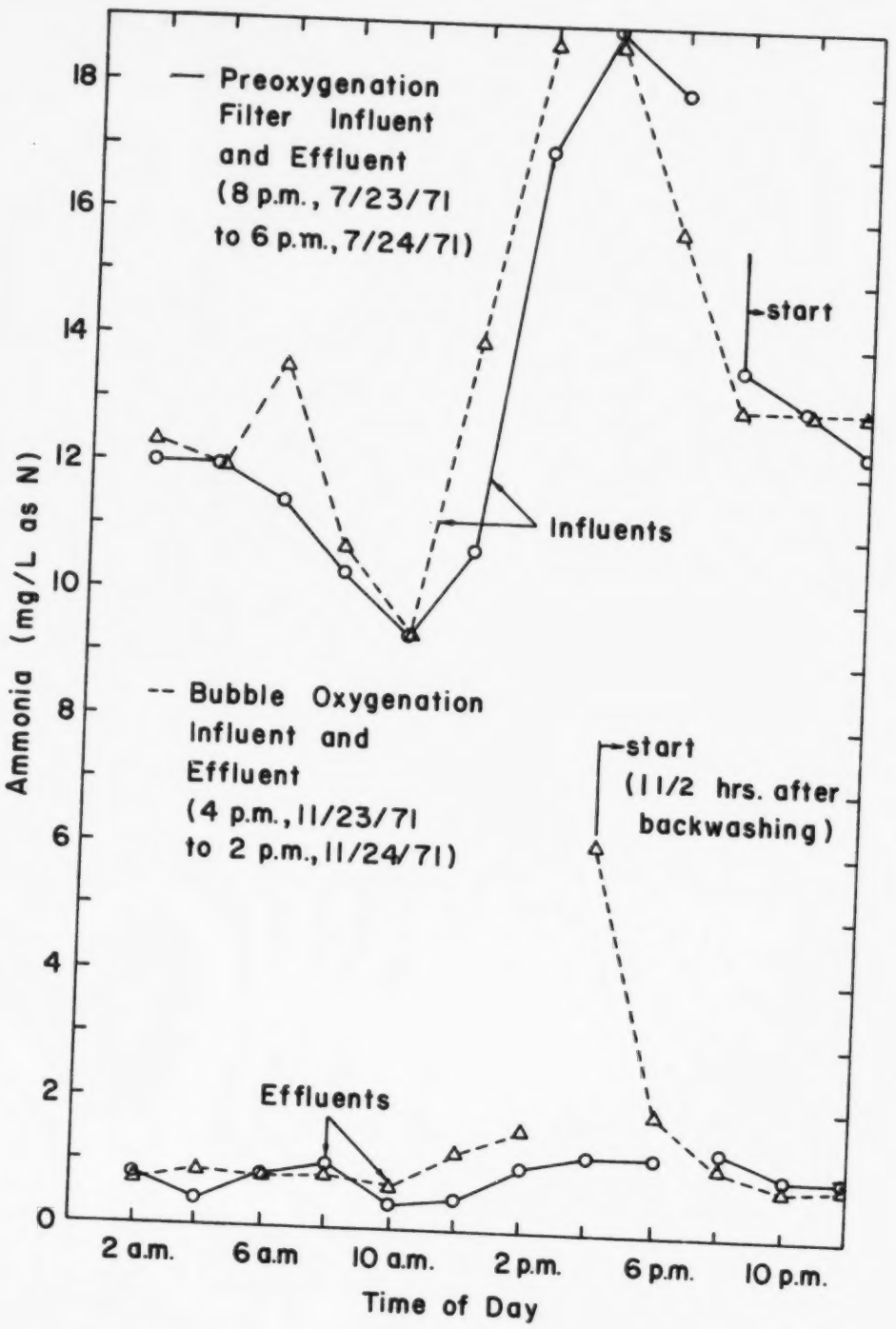

Figure 16. Ammonia nitrogen variations over 24-hour periods.

start of the bubble oxygenation sampling was caused by backwashing 1-1/2 hours prior to the start of sampling. Discounting the affect of this both filters averaged 93 percent ammonia nitrogen removal and both were able to oxidize a 9.3 to 19.0 mg/l range of influent ammonia nitrogen with consistent results. It should also be noted that the influent ammonia nitrogen concentrations were very similar over the 24-hour period even though the two studies were made four months apart. The weakest and strongest sewage with respect to ammonia nitrogen occurred at 10 a.m. and 3 to 4 p.m, respectively. This corresponds to a flow time of 0.5 to 5 hours in the trunk line sewer and 3.5 to 8 hours through the principal secondary treatment plant. More detailed analytical data can be found in Appendix D.

Effluent Nitrogen Forms

While it was possible to obtain 90 percent removal of ammonium nitrogen in the submerged filter, it would be much more difficult to meet a strict effluent standard with respect to all unoxidized forms of nitrogen (NH_4^+-N, NO_2^--N and Organic-N). There was a concentration of 3.1 mg/l and 4.3 mg/l of total unoxidized nitrogen in the average effluent from the preoxygenation and bubble oxygenation filters, respectively, when operated at a 60 minute detention time (Table 19). This difference between the two filter systems is not meaningful because of inadequate data on the bubble oxygenation system. In either case the soluble organic nitrogen equalled about 50 percent of the remaining unoxidized nitrogen.

This soluble organic nitrogen must be fairly refractory in form since it was unaffected by two stages of biological treatment. Even if complete inorganic nitrogen oxidation were achieved this soluble organic nitrogen would remain in the final effluent. It is not known whether the soluble organic nitrogen could stimulate algal growth, or whether the organics with which it is associated would eventually be decomposed and the nitrogen released as NH_3. Any proposed effluent standard for total nitrogen should consider the presence of this soluble organic nitrogen and the current limitation of methods for its removal. Research concerned with the nature of the soluble organic nitrogen and methods for its removal is needed.

TABLE 19

EFFLUENT NITROGEN FORMS REMAINING AFTER NITRIFICATION

	Detention Time(min)	Effluent Nitrogen (mg/l) NH_4^+-N	NO_2^--N	NO_3^--N	Org-N Total	Org-N Sol.	Total-N
Preoxygenation Filter:							
Average	60	1.0	0.6	15.9	1.5	-	19.5
No. of Samples	-	8	8	8	8	-	8
Std. Deviation	-	±0.4	±0.4	± 3.0	±0.7	-	± 2.8
Average	30	6.9	1.7	6.0	2.5	2.2	17.1
No. of Samples	-	11	11	11	5	3	-
Std. Deviation	-	±3.1	±1.3	± 2.8	±0.5	-	-
Bubble Oxygenation Filter:							
Average	60	1.8	0.4	18.4	4.6	2.1	25.2
No. of Samples	-	8	7	7	1	1	-
Std. Deviation	-	±1.0	±0.1	±3.8	-	-	-

SECTION VII

SUMMARY AND DISCUSSION

This section contains first a brief review of the important aspects of submerged filter operation. Following this a comparison is made between the results of the previous laboratory study and the field study. Next a method of calculating the necessary recycle ratio for the preoxygenation system is developed and demonstrated. Finally a brief discussion is presented on the magnitude of the unoxidized nitrogen from which remain after nitrification.

The unchlorinated effluent from a full scale 3 mgd activated sludge plant was used as the influent of the field submerged rock filters. This activated sludge plant influent flow consisted of 80 to 85 percent domestic sewage.

Operating Results

Preoxygenation Filter With Recycle. At a 60 minute detention time during the initial start-up period, a 90 percent or greater ammonia nitrogen removal was consistently attained after 60 days of filter operation. Normal steady state operation resulted in a 90 to 96 percent ammonia nitrogen removal at temperatures ranging from 21 to 27 ^{o}C.

The submerged filter also acted as an excellent polishing device for the activated sludge effluent. It accomplished an additional 75 to 95 percent reduction in BOD_5; a 46 to 58 percent reduction in COD; and an 84 to 96 percent reduction in suspended solids.

Gravity backwashing twice per week a rate of 6 to 20 gal/ft^2/min prevented the filter from clogging over a 3-1/2 month period of operation at a 60 minute detention time. These rates of backwashing were not adequate to prevent clogging at the shorter detention times of 30 to 40 minutes.

Bubble Oxygenation Filter. At a 60 minute detention time during the initial start-up period 90 percent ammonia nitrogen removal was attained after 70 days of filter operation. Normal steady state operation resulted in an 87 to 95 percent ammonia nitrogen removal at temperatures ranging from 16 to 30 ^{o}C.

There was also a 67 to 87 percent reduction in BOD_5; a 47 to 59 percent reduction in COD; and an 8 to 88 percent reduction in suspended solids. The tubulence caused by rising oxygen bubbles resulted in the continuous discharge of a variable concentration of suspended solids to the filter effluent. No clogging problems occurred with this filter during a 6 month period of operation. There was a need, however, to waste excess solids about once per week.

Comparison Between the Preoxygenation and the Bubble Oxygenation Filter. After 2 months of operation at 60 minute detention time the preoxygenation filter was able to attain 93 $\pm$ 3 percent ammonia nitrogen removal while the bubble oxygenation filter attained a 91 $\pm$ 4 percent removal, probably an insignificant difference. The preoxygenation filter was slightly superior in BOD and COD removal and much better in suspended solids removal.

Clogging was not a problem when either filter was operated for a 3-1/2 month period at a 60 minute detention time. During this time the preoxygenation filter was backwashed by gravity draining at a rate of 6 to 20 gal/ft^2/min (usually the lower rate) twice per week. There is a possibility of clogging problems occurring with high influent BOD_5 (> 50 mg/l) and suspended solids (> 50 mg/l), or through operation over longer periods of time. However, these potential problems most likely could be prevented by daily gravity backwashing. At a 30 to 40 minute detention time gravity backwashing proved to be unsuccessful in preventing clogging with the preoxygenation filter. However, clogging was never a problem in the bubble oxygenation filter.

After a 2 day idle aerobic period both filters were able to obtain normal ammonia nitrogen removal efficiencies within a 24 hour period. After the preoxygenation filter went partially anaerobic for 1 to 2 days normal removal efficiencies were regained within a 2 week period. When the bubble oxygenation filter went very anaerobic (black sludge) for at least 2 days, normal operation was attained within 3 weeks. The preoxygenation filter is superior to the bubble oxygenation filter in recovery from anaerobic conditions because there are no rising oxygen bubbles to discharge bacterial solids which become loosened from the stone surfaces under such conditions.

Both filters contained biological organisms typical in appearance to those associated with the activated sludge process. Numerous nematodes along with amoebae, rotifers, and stalked and free-swimming ciliate protozoa were present.

Suspended Solids Accumulation in the Filter. The accumulation of suspended solids in the filter is an important consideration as they must be removed to prevent clogging and they also add a small but significant quantity of sludge for subsequent disposal. Most of the influent suspended solids are removed from the waste stream by the filter. Additional biological suspended solids are produced within the filter in association with the biological oxidation of soluble wastewater organics and nitrification. Also, a portion of the accumulated suspended solids are oxidized within the filter.

There were three different approaches used to estimate the amount of suspended solids accumulation in the preoxygenation filter. These different methods all suggested that the suspended solids in the influent accounted for the major fraction of the accumulated suspended solids.

However, formation of biological suspended solids from soluble organic oxidation and nitrification resulted in the accumulation of 10 to 20 mg of volatile suspended solids per liter of waste, which is a quantity worthy of consideration. Thus, for example, if the waste flow rate were 10 mgd and the suspended solids in the influent to the filter were 30 mg/l, and assuming 87 percent removal were obtained by the filter, then the accumulation would equal 10(8.34)[0.87(30) + 15] or 3,400 pounds per day. The value 15 is an estimate of the suspended solids produced from soluble COD removal and nitrification. Surprisingly, only a small fraction of the suspended solids removed were oxidized in the filter. The efficiency of suspended solids capture was much less with the bubble oxygenation filter so that suspended solids accumulation was much lower.

Comparison of the Results from the Field and Laboratory Studies

Preoxgenation Filter. A 90 percent ammonia nitrogen removal required a 57 minute detention time in the field study, but only a 27 minute detention time in the laboratory study (Figure 17). The curve representing results from the laboratory study was generated using Equation 14 and temperatures equivalent to the average field temperatures (22 and 25 °C).

There are four reasons which can be given to explain the above differences in results. First, the actual detention time in the field filters was shorter than the theoretical time because of a larger suspended solids accumulation, which resulted in less void space and greater short-circuiting of flow. Second, in the field study there was competition and spatial interference between the nitrifying bacteria and the other suspended solids which accumulated in the filter. It was estimated that only about 10 percent or less of the suspended solids in the filter were actually nitrifying bacteria during normal operating conditions at a 60 minute detention time in the field, while this fraction approached 100 percent in the laboratory study.

A third reason for lower efficiencies in the field study is the greater wash-out rate of nitrifying bacteria (reduced biological solids retention time) due to the need to frequently remove accumulated suspended solids from the filter in the field. A high wash-out rate was not necessary in the laboratory because the influent contained no suspended solids.

A fourth possible factor (probably minor) is the slower diffusion rate of oxygen and/or ammonia in secondary effluent as compared with tap water (14).

Bubble Oxygenation Filter. A significantly longer detention time was also required in the field than in the laboratory with this filter in order to obtain the same degree of ammonia nitrogen removal (Table 20). At a detention time of 60 minutes in the field a 91 $\pm$ 4 percent ammonia nitrogen removal was obtained while 95 percent removal was obtained in the laboratory study. At shorter detention times the field filter lost removal efficiency rapidly while the laboratory filter efficiency remained reasonably high, very similar to the preoxygenation case.

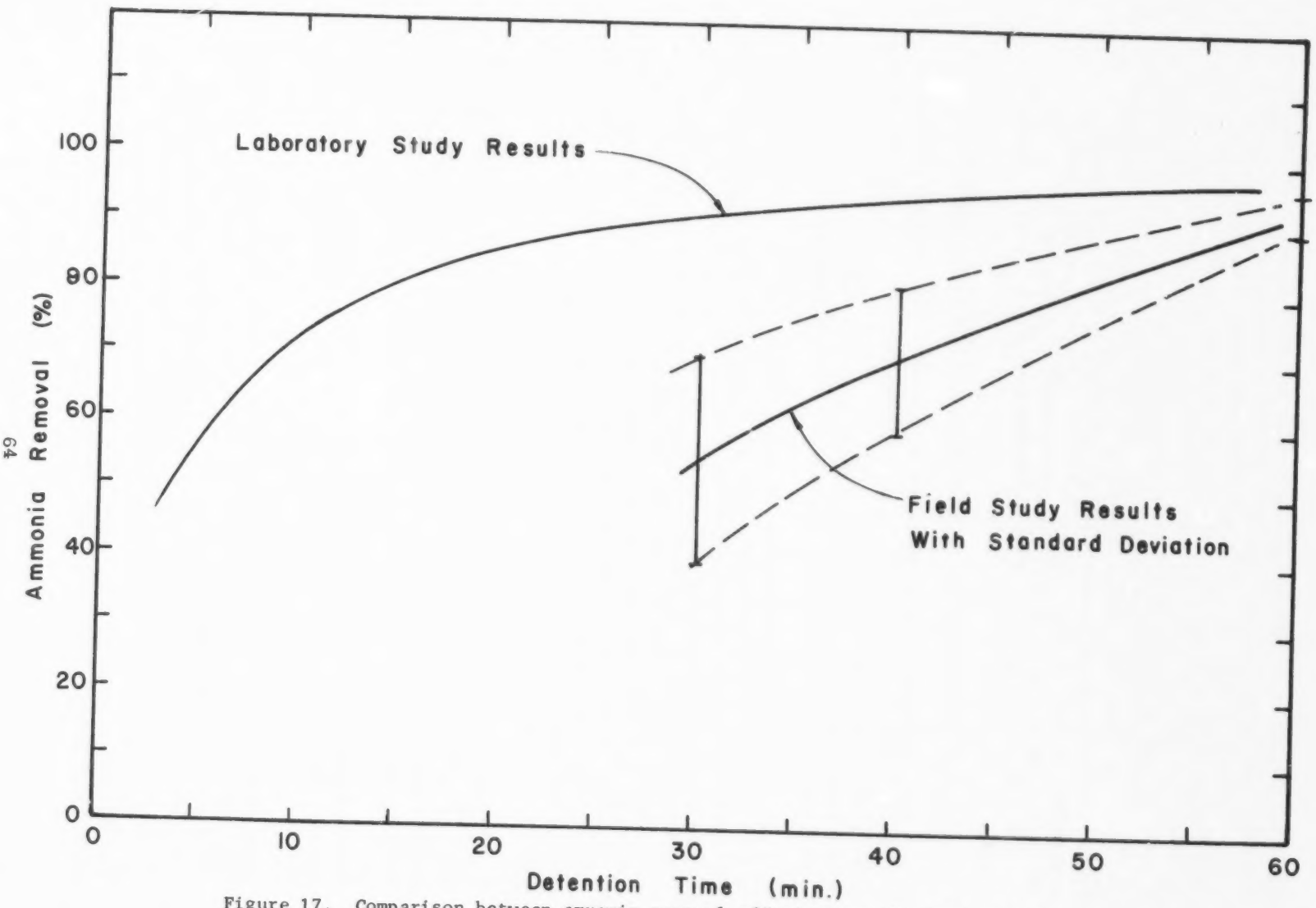

Figure 17. Comparison between ammonia removal efficiencies obtained in the laboratory and in the field studies with the preoxygenation filter.

TABLE 20

COMPARISON OF LABORATORY AND FIELD RESULTS

(Bubble Oxygenation Filter)

	Percent Removal NH_3-N	
Detention Time (min)	Laboratory	Field
30	89	40-50 *
60	95	91

* Data Collected during the time of high influent S.S.

Backwashing was never required in the laboratory study for this filter, but was required in the field study to keep solids from building-up in the base of the filter.

The required oxygen flow rate varied from 0.08 to 0.125 cfm/ft^2 in the field study but was only 0.017 to 0.043 cfm/ft^2 in the laboratory study. Part of this difference was reflected in the additional 25 to 30 percent oxygen demand by the organic matter in the field study influent. Also, the efficiency of oxygen transfer tends to decrease as the level of organic matter increases in the wastewater. In actual field practice a much higher percent of oxygen transfer could be obtained with smaller bubbles, deeper filters and most important, oxygen recycle.

Recycle Ratio

Wastewater recycle must be used with the preoxygenation submerged filter for any waste with an ammonia nitrogen concentration greater than 8 to 10 mg/l or a total oxygen demand greater than the oxygenation capacity of the system. A reasonable assumption is that the total dissolved oxygen available, TOA, in the influent to the filter should be equal to or greater than the combined total oxygen demand of the mixture of the raw influent waste and the recycled effluent in order to obtain a maximum rate of nitrification (Figure 18). This assumption is based on the finding that the maximum rate of nitrification occurred in the laboratory submerged filters when the dissolved oxygen concentration was stoichiometrically equal to or greater than the ammonia nitrogen oxygen requirement (2). Based on this assumption, the following relationship can be developed:

$$TOA \geq TOD_i = \frac{TOD_w + R(TOD_e)}{1 + R} \qquad (15)$$

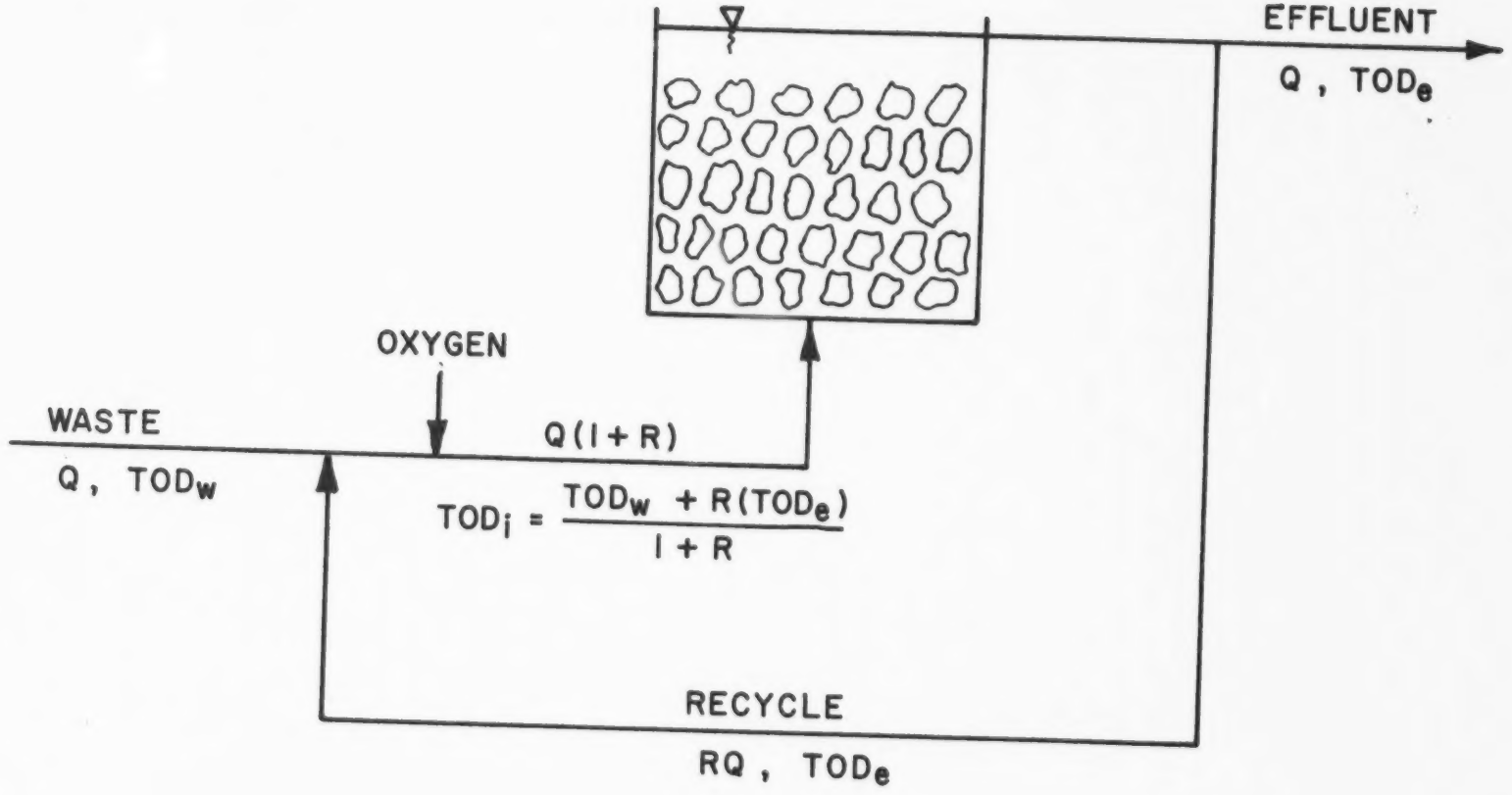

Figure 18. Flow through submerged filter with recycle.

where TOA - total dissolved oxygen added; the maximum value obtainable is a function of pressure, temperature, dissolved solids and the percent of oxygen saturation which can be achieved in the wastewater.

TOD_w - total oxygen demand of the influent wastewater.

TOD_e - total oxygen demand of the effluent wastewater.

TOD_i - total oxygen demand of the combined raw wastewater and recycled effluent entering the filter.

R - recycle ratio = recycle flow rate/influent wastewater flow rate.

By letting $TOA = TOD_i$ the above equation can be solved to obtain the minimun recycle ratio:

$$R_{min} = \frac{TOD_w - TOA}{TOA - TOD_e} \qquad (16)$$

TOD_w and TOD_e are functions of the ammonia nitrogen, nitrite nitrogen, and BOD concentrations in the influent and effluent, respectively. In the results section, the oxidation of organic matter within the preoxygenation filter was discussed. It was found that the oxygen demand due to BOD oxidation averaged about 0.63 times the BOD_5 concentration. Using a conservative estimate, the oxygen demand due to organic oxidation within the filter will be assumed to equal the BOD_5.

On this basis a detailed expression for the minimum required recycle ration is:

$$R_{min} = \frac{(4.57[NH_3\text{-}N] + BOD_5)_w - TOA}{TOA - (4.57[NH_3\text{-}N] + BOD_5)_e} \qquad (17)$$

The term $(4.57[NH_3\text{-}N] + BOD_5)_e$ represents a concentration of dissolved oxygen in the effluent large enough to insure the maximum oxidation rate in the filter of both ammonia nitrogen and carbonaceous BOD. If NH_3-N oxidation is of primary concern it appears not necessary to insure that the dissolved oxygen concentration be greater than the stoichiometric requirement for ammonia nitrogen oxidation throughout the filter. Therefore, the additional effluent dissolved oxygen for $(BOD_5)_e$ oxidation did not seem necessary and so this term was eliminated from the above equation. This assumption needs verification. Onthis basis, the final equation used is:

$$R_{min} = \frac{(4.57[NH_3\text{-}N] + BOD_5)_w - TOA}{TOA - (4.57[NH_3\text{-}N])_e} \qquad (18)$$

To be precise 1.14(NO_2-N) should be subtracted from the numerator of the above equation. Usually the effluent nitrite nitrogen concentration is so small that complete oxidation of all ammonia nitrogen to nitrate nitrogen can be assumed for practical purposes.

An example calculation is given to demonstrate the use of this equation:

Given: $(NH_3\text{-}N)_w = 15$ mg/l $\quad (NH_3\text{-}N)_e = 1.5$ mg/l

$(BOD_5)_w = 30$ mg/l $\quad (BOD_5)_e = 5$ mg/l

Temperature = 22 °C $\quad$ Pressure = 1 atm

Oxygen gas which is 99.5 percent pure is used.

Percent oxygen saturation obtained by oxygenation = 75.

Air is 20.9 percent oxygen.

Required: Find the minimum recycle ratio.

Solution:

1) $$TOA = \begin{pmatrix}\text{atm.}\\ \text{press.}\end{pmatrix}\begin{pmatrix}\%\ O_2\\ \text{sat.}\end{pmatrix}\begin{pmatrix}\%\ O_2\\ \text{in gas}\end{pmatrix}\left(\frac{100}{20.9}\right)\begin{pmatrix}\text{Sol. of}\\ \text{air in}\\ H_2O\end{pmatrix}$$

$$= (1)(0.75)(0.995)\ \frac{100}{20.9}\ (8.9)$$

$$= 31.7 \text{ mg/l}$$

2) $$\text{Recycle Ratio} = \frac{\left[4.57(NH_3\text{-}N) + BOD_5\right]_w - TOA}{TOA - \left[4.57(NH_3\text{-}N)\right]_e}$$

$$= \frac{4.57(15) + 30 - 31.7}{31.7 - 4.57(1.5)} = 2.7$$

The above conditions were close to the operating conditions of the 60 minute detention time field preoxygenation filter. If the ammonia nitrogen concentration is raised to 20 mg/l the recycle ratio rises to 4.0. If the temperature falls to 15 °C then the recycle ratio falls to 2.1 because of the greater solubility of oxygen.

Advantages of the Submerged Filter

The most important advantage of the submerged filter is its simplicity in both design and operation. It has advantages over the suspended growth nitrification process (activated sludge type) in that it requires less detention time and has a longer solids retention time. Biological

solids separation in a final clarifier and sludge return are not needed for either the preoxygenation filter or bubble oxygenation filter. Since these filters have a solids retention time similar to that of a trickling filter they need less supervision than a suspended growth reactor. In addition, the laboratory study results indicate nitrification can be achieved reliably in the filter at temperatures near the freezing point of water.

Both the preoxygenation filter with recycle and the bubble oxygenation filter provide a significant degree of BOD and COD reduction. The preoxygenation filter also provides a low suspended solids effluent, superior to that from most clarifiers commonly used with the activated sludge process.

The long solids retention time allows for stable nitrification at varying temperatures, ammonia nitrogen concentrations, pH and flow rates. The submerged filter is well suited to the treatment of intermittent waste discharges if the filter remains aerobic during periods of idleness. Following periods without influent waste, on the order of a few days, rapid secondary starting is possible.

Disadvantages of the Submerged Filter

The major disadvantage of the submerged filter is the potential clogging problem. Based on present technology, it is quite likely that a preoxygenation submerged filter would not be able to receive an influent with an extremely high BOD and suspended solids concentration (> 60 to 80 mg/l) because of this problem. However, the problem is minimized in a bubble oxygenation filter, although at the sacrifice of effluent quality. In addition, the higher the organic load on the filter the lower will be the percentage of nitrifying bacteria within the suspended solids in the filter, and thus, the longer the required detention time for a given efficiency of nitrification.

Another possible disadvantage is the high cost for oxygen. An efficient method of oxygen transfer (preoxygenation) or a good method for capture of oxygen for recycle (bubble oxygenation) is needed to reduce this cost to a minimum. High concentrations of oxygen in the effluent from the bubble oxygenation system may represent a wastage of oxygen.

Estimated Cost of Treatment

Since experience with full scale submerged filters is lacking, many assumptions have to be made in order to estimate costs of operation. An influent ammonia nitrogen concentration of 20 mg/l and an influent BOD concentration of 30 mg/l are assumed for estimating purposes along with 2 hour detention time in the filter (two stages). Annual cost data are based on the year 1972 using a 5.5 percent interest rate for a 20 year design period. A summary of cost data for the bubble

oxygenation filter reveals a total cost of 3.9, 2.5, 2.2 cents/1000 gal for a 5, 20 and 100 mgd plant, respectively. The preoxygenation filter with recycle has slightly higher costs of 4.8 to 2.8 cents/1000 gal in the range of 5 to 100 mgd. A typical example of cost estimate for a 20 mgd plant is given in Table 21.

The total cost of treatment includes capital and operation and maintenance costs. The capital costs can be divided into the categories of filter rock, a structure to contain the rock, oxygen transfer equipment, yard piping, pumps, motors, and finally administrative, engineering and contingency costs.

For two hour detention time, 28,800 ft^3 of rock are required (at 39 percent void volume) per 1 mgd of treatment capacity. This rock should be of quality similar to that of trickling filter rock but with a diameter of 1 to 2 inches. The rock specifications should involve values for the Los Angeles Abrasion Test for Wear, the Sodium Sulfate Loss Test (ASCE Manual 13) and the Adsorption Test (ASTM C127) (19). The filter rock should be free of organic matter, soil, clay and any thin or elongated flat pieces of rock. The installed cost would be approximately \$0.18/ft^3 of rock (19).

Another capital cost consideration is a water tight tank to contain and support the rock. It will be assumed that the filter would be partitioned off into 20x20 feet compartments to facilitate efficient backwashing. No separate backwashing reservoir will be used in this calculation. The filter structure consists of the tanks, foundation and influent distribution and effluent collection systems. Based on cost figures for designing a similar anaerobic filter a structure cost of \$0.90/ft^3 of rock will be used (19).

The oxygen transfer equipment includes blowers, motors, air piping and instrumentation. The selection of the oxygen transfer equipment for the bubble oxygenation filter was based on 90 percent oxygen utilization efficiency. About 65 percent of the oxygen transfer will occur in the first stage and 35 percent in the second stage. The recycled gas would contain about 75 percent oxygen in the first stage and 55 percent in the second stage. The required blower horsepowers for the 5, 20, and 100 mgd plant are 50, 250, and 820, respectively. The preoxygenation filter oxygen transfer equipment costs include a significant amount of capital costs for a separate oxygen transfer chamber (17).

A fourth cost consideration is yard piping, pumps and miscellaneous items. The preoxygenation system and bubble oxygenation system differ with respect to pump requirements. It is possible to operate the bubble oxygenation filter without pumps, while the preoxygenation filter requires recycle pumps capable of providing a recycle ratio of 4. Yard piping is another highly variable design consideration.

The fifth and last capital cost consideration is the 30 percent administration, engineering and contingency charge that is applied to the above costs.

TABLE 21

ESTIMATE OF FILTER COST*
(20 mgd)

System Costs	Preoxygenation Filter	Bubble Oxgenation Filter
I. Capital Costs		
A. Filter Rock Installed ($0.18/ft^3)	$103,200	$103,200
B. Filter Tank Structure	517,000	517,000
C. Oxygen Transfer Equipment	400,000+	60,800
D. Yard Piping, Pumps, etc.	80,800	36,000
Sub-total:	1,101,000	717,000
E. Adminstration, Engineering (Contingencies [30%])	330,000	215,000
Total Capital Cost:	1,431,000	932,000
Average Annual Cost (crf - 5.5-20)	120,000	77,700
Cents/1000 gal.	1.7	1.1
Dollars/ft^3 of filter	2.49	1.62
II. Operation and Maintenance Cost (Annual)		
A. Oxygen	69,000	69,000
B. Oxygen Transfer Equipment	12,000	12,000
C. Labor	30,000	20,000
Total O & M Cost (annual):	111,000	101,000
Cents/1000 gal.	1.5	1.4
Total Cents/1000 gal.	3.2	2.5

* Not including land cost, site preparation or unusual excavation problems.

\+ Only approximate.

The operation and maintenance costs associated with the submerged filter include oxygen costs, oxygen transfer equipment operational costs, other operational costs and labor. At the use rates of oxygen projected, on site oxygen production appears to be the most economical ($16 to $20 per ton). Assuming a total oxygen demand of 125 mg/l and 90 percent oxygen utilization efficiency about 0.58 tons of oxygen are required per million gallons of treated wastewater. The cost per ton of oxygen is described in detail elsewhere (17). The preoxygenation system requires a greater quantity of electricity to operate the low head recycle pumps.

The costs for oxygen, filter rock and oxygen transfer equipment are reasonably accurate, but the estimated costs for the filter tank, yard piping, pumps, engineering and labor can be highly variable depending on the individual design conditions. The major costs items are oxygen and the filter structure for the bubble oxygenation filter.

SECTION VIII

ACKNOWLEDGEMENTS

Appreciation is extended to Mr. Robert Hiles, Operation Superintendent, Union Sanitary District, Newark, California, for his support of this project and for making the facilities of the District Treatment Plant No. 3 available for conducting this study. Mr. Arthur Duarte, Assistant Operating Superintendent, was most helpful in making necessary arrangements for the study and for furnishing operating data for the treatment plant. Special thanks go to Mr. John Silva, Supervisor of Plant No. 3, and the operating personnel for their interest in the study and willingness to help whenever possible.

The director of the project was Dr. Perry L. McCarty, Professor of Civil Engineering, Stanford University, Stanford, California. Mr. Donald D. McHarness supervised the field studies and prepared the draft of this report. He was assisted by Mrs. Victoria Mongird, who conducted many of the analytical tests, and Mr. Deepak Bajracharya, who helped in the general operation of the field units. The pilot plant was constructed by Mr. Kevin Clancy. Dr. Roger T. Haug, who supervised the laboratory portion of this overall study, also assisted in devising the study plan and in helping to conduct the initial phases of the filter operation.

The support of this project by the Environmental Protection Agency, and the assistance provided by Mr. Edwin F. Barth, the Grant Project Officer, is greatly appreciated.

SECTION IX

REFERENCES

1. Courchaine, R. J., "Significance of Nitrification in Stream Analysis-Effects on the Oxygen Balance," Jour. Water Poll. Control Fed., Vol 40, No. 5, 835-47, (May 1968).

2. Haug, R. T. and McCarty, P. L., Nitrification With the Submerged Filter, Technical Report No. 149, Department of Civil Engineering, Stanford University, (August 1971).

3. "Nitrification in the BOD Test," Notes on Water Pollution, No. 52, Water Pollution Research Laboratory, Stevenage, England, (March 1971).

4. Haug, R. T. and McCarty, P. L., Nitrification With the Submerged Filter, Presented at the Annual Conference of the Water Pollution Control Federation, San Francisco, California (October 1971).

5. Wild, H. E., Sawyer, C. N. and McMahon, T. C., "Factors Affecting Nitrification Kinetics," Jour. Water Poll. Control Fed., Vol. 43, No. 9, 1845-54, (September 1971).

6. Monod, J., "The Growth of Bacterial Cultures," Annual Review of Microbiology, Vol. 3, 371, (1949).

7. Michaelis, L. and Menton, M. L., "Kinetics of Invertase Action," Biochem. Zeit., Vol. 49, 333-369, C.A.7, No.2232, (1913).

8. Scatton, Frank E., Nitrification Effects on Oxygen Resources in Streams, Ph.D. Thesis, Stanford University, (July 1969).

9. Standard Methods for the Examination of Water and Wastewater, 12th Ed., American Public Health Assoc., Inc., New York, (1965).

10. Standard Methods for the Examination of Water and Wastewater, 13th Ed., American Public Health Assoc., Inc., New York, 464, (1971).

11. Wycoff, B. M., "Rapid Solids Determination Using Glass Fiber Filters," Water and Sewage Works, Vol. 111, No. 6, 277, (June 1964).

12. Sawyer, C. N. and McCarty, P. L., Chemistry for Sanitary Engineers, 2nd Ed., McGraw-Hill Book Co., San Francisco, (1967).

13. Skoog, D. A. and West, D. M., Fundamentals of Analytical Chemistry, 2nd Ed., Holt, Rinehart and Winston, Inc., San Francisco, 670, (1969).

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14. Eckenfelder, Jr., W. Wesley, Industrial Water Pollution Control, McGraw-Hill Book Co., San Francisco, 62-3, (1966).

15. Mulbarger, M.C., "Nitrification and Denitrification in Activated Sludge System," Jour. Water Poll. Control Fed., Vol. 43, No. 10, 2059-70, (October 1971).

16. Speece, R. E. and Adams, J. L., "U-tube Oxygenation Operating Characteristics," Proceedings of the 23th Industrial Waste Conference, Purdue University, May 7, 8, and 9, 195-212, (1968).

17. Investigation of the Use of High-Purity Oxygen Aeration in the Conventional Activated Sludge Process, Water Pollution Control Research Series No. 17050 DNW05/70, by Union Carbide Corp., Linde Division, Tonawanda, New York, (May 1970).

18. Speece, R. E., "The Use of Pure Oxygen in River and Impoundment Aeration," Proceedings of the 24th Industrial Waste Conference, Purdue University, May 6, 7, and 8, 700-12, (1969).

19. Peterson, Ralph R., Cornell, Howland, Hayes and Merryfield, and Clair A. Hill and Associates, Corvallis, Oregon, (Personal Correspondence).

20. Heukelekian, H., "The Relationship Between Accumulation, Bio-Chemical and Biological Characteristics of Film, and Purification Capacity of a Bio-filter and a Standard Filter," Sewage Works Journal, Vol. 17, 516 (1945).

SECTION X

PUBLICATIONS

1. Haug, T. R. and McCarty, P. L., Nitrification with the Submerged Filter, Technical Report No. 149, Department of Civil Engineering, Stanford University, (August 1971).

2. Haug, R. T. and McCarty, P. L., "Nitrification with the Submerged Filter," Journal Water Pollution Control Federation, In Press.

SECTION XI

LIST OF SYMBOLS

a	=	Regression coefficient, Y-intercept or rate constant.
b	=	Regression coefficient, slope or order of reaction.
BOD	=	Standard 5-day 20 ^{o}C biochemical oxygen demand.
COD	=	Standard chemical oxygen demand.
DO	=	Dissolved oxygen concentration, mg/l.
k	=	Maximum utilization coefficient, mass/time-mass.
K_s	=	The "half-velocity coefficient," the substrate concentration at which the rate of reaction is one-half the maximum rate, mass/volume.
R	=	Recyle ratio, recycle flow rate/untreated waste flow rate.
R_{min}	=	Minimum required recycle ratio for the submerged filter.
S	=	Substrate concentration, mass/volume.
S_b	=	Substrate concentration in the bulk liquid phase outside the bio-film, mass/volume.
S_e	=	Effluent NH_3-N concentration from submerged filter, mass/volume.
S_f	=	Substrate concentration in the bio-film, mass/volume.
S_i	=	Substrate concentration at the liquid-film interface, or influent NH_3-N concentration to the submerged filter after mixing of untreated and recycle flows, mass/volume.
S_o	=	Substrate concentration at the film-media interface, mass/volume.
S.S.	=	Suspended solids concentration, mass/volume.
S_w	=	Untreated waste NH_3-N concentration, mass/volume.
TOA	=	Total dissolved oxygen concentration added by preoxygenation, mg/l.

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TOD_e = Total oxygen demand of the effluent from the submerged filter, mg/l.

TOD_i = Total oxygen demand of the combined untreated and recycled wastewaters entering the submerged filter, mg/l.

TOD_w = Total oxygen demand of the untreated influent wastewater, mg/l.

X = Concentration of active microorganisms, mass/volume.

SECTION XII

APPENDICES

Page

A. Wastewater characteristics and treatment efficiencies for the Union Sanitary District Plant No. 3 during the period of this study.

Table A-1: Average monthly effluent quality for the Union Sanitary District Plant No. 3. 83
Table A-2: Periodic analysis of wastewater characteristics and treatment efficiency at the Union Sanitary District Plant No. 3. 84
Table A-3: Typical nitrogen concentration changes through the Union Sanitary District Plant No. 3. . . . 85
Table A-4: Concentration of ammonia and organic nitrogen in effluent from Union Sanitary District Plant No. 3. 85

B. Summaries of results from operation of preoxygenation filter and bubble oxygenation filters.

Table B-1: Summary of results for preoxygenation filter at 60 minute detention time. 86
Table B-2: Summary of results for preoxygenation filter at 40 minute detention time. 87
Table B-3: Summary of results for preoxygenation filter at 30 minute detention time. 88
Table B-4: Summary of results for bubble oxygenation filter at 60 minute detention time. 89

C. Detailed analytical results from operation of preoxygenation and bubble oxygenation filters.

Table C-1: Nitrogen data for preoxygenation filter at 60 minute detention time. 90
Table C-2: Miscellaneous data for preoxygenation filter at 60 minute detention time. 91
Table C-3: Nitrogen data for preoxygenation filter at 40 minute detention time. 92
Table C-4: Miscellaneous data for preoxygenation filter at 40 minute detention time. 93
Table C-5: Nitrogen data for preoxygenation filter at 30 minute detention time. 94
Table C-6: Miscellaneous data for preoxygenation filter at 30 minute detention time. 95
Table C-7: Nitrogen data for bubble oxygenation filter at 60 minute detention time. 96
Table C-8: Miscellaneous data for bubble oxygenation filter at 60 minute detention time. 97
Table C-9: Nitrogen data for bubble oxygenation filter at 30 minute detention time. 98
Table C-10: Miscellaneous data for bubble oxygenation filter at 30 minute detention time. 99

Page

D. Detailed data obtained during 24-hour study of filter operation.

Table D-1: Preoxygenation filter. 100
Table D-2: Bubble oxygenation filter. 101

TABLE A-1

AVERAGE MONTHLY EFFLUENT QUALITY FOR THE UNION SANITARY DISTRICT PLANT NO. 3 (1).

Month	Flow MGD	Effluent (24 hour composite) Susp. Sol. (mg/l) Ave.	Low	High	BOD_5 (mg/l) Ave.	Low	High	Influent pH (Grab) High	Low
1971:									
May	2.3	18	11	27	26	12	52	7.8	7.4
June	2.4	23	12	42	32	7	60	7.9	7.2
July	2.3	22	14	43	36	27	51	7.7	7.2
August	2.4	34	18	114	43	28	77	7.9	6.7
September	2.5	29	19	102	42	30	94	7.9	7.1
October	2.3	40	26	63	46	33	63	7.8	7.4
November	2.4	59	33	144	55	39	88	7.9	7.3
December	2.6	55	26	94	46	20	64	-	-
1972:									
January	2.6	69	28	124	56	40	90	-	-

(1) Collection and analysis performed by Union Sanitary District.

TABLE A-2

PERIODIC ANALYSIS OF WASTEWATER CHARACTERISTICS AND TREATMENT EFFICIENCY AT THE UNION SANITARY DISTRICT PLANT NO. 3 (3).

Date	Suspended Solids			Grease			BOD_5			COD		
	Inf.[1] mg/l	Eff.[2] mg/l	Percent Removed	Inf.[1] mg/l	Eff.[2] mg/l	Percent Removed	Inf.[1] mg/l	Eff.[2] mg/l	Percent Removed	Inf.[1] mg/l	Eff.[2] mg/l	Percent Removed
5/20/71	273	17	94	99	1.6	98	207	23	89	634	104	84
6/23/71	247	32	81	92	3.6	96	193	39	80	622	117	81
7/22/71	272	25	91	84	5.8	93	215	29	86	602	133	78
8/18/71	435	43	90	84	4.7	94	427	41	90	863	135	84
9/21/71	301	25	92	96	3.6	96	211	33	84	660	140	79
10/20/71	223	40	82	90	9.4	89	188	53	72	618	187	70
11/23/71	267	41	85	215	6.5	97	205	51	75	701	180	74
12/16/71	-	-	-	128	5.5	94	-	-	-	715	176	75
1/9/72	-	-	-	105	12.1	88	-	-	-	872	235	73

(1) 8 hour composite (8:00 a.m. - 4:00 p.m.).

(2) 24 hour composite.

(3) Collection and analysis performed by Union Sanitary District.

TABLE A-3

TYPICAL NITROGEN CONCENTRATION CHANGES THROUGH THE UNION SANITARY DISTRICT PLANT NO. 3.

(November 23-24, 1971) (1)

Parameter	Raw Sewage	Vacuator Effluent	Final Effluent
NH_3-N(mg/l)	15.0	16.2	13.7
NO_2^--N(mg/l)	0.3	0.0	0.2
NO_3^--N(mg/l)	0.05	0.1	0.2
Org-N(mg/l)	14.4	19.3	8.8
Total-N(mg/l):	29.7	35.6	22.9

TABLE A-4

CONCENTRATION OF AMMONIA AND ORGANIC NITROGEN IN EFFLUENT FROM UNION SANITARY DISTRICT PLANT NO. 3 (3).

Month	Ammonia-N mg/l				Organic-N mg/l			
	Number of Samples	Ave.[1]	High[2]	Low[2]	Number of Samples	Ave.[1]	High[2]	Low[2]
1971:								
June	8	15.4	-	11.7	4	3.8	-	1.8
July	17	15.8	19.0	9.3	4	4.8	-	3.1
August	6	14.6	-	10.7	2	5.5	-	-
September	9	16.2	20.8	9.6	1	6.2	-	-
October	5	18.4	25.9	12.5	-	-	-	-
November	17	18.3	23.0	9.3	1	8.8	-	-
December	5	16.8	23.9	-	0	-	-	-
1972:								
January	7	18.7	31.2	-	0	-	-	-

(1) 24-hour composite samples.
(2) Grab samples.
(3) Influent nitrogen concentration to field nitrification filter.

TABLE B-1

SUMMARY OF RESULTS FOR PREOXYGENATION FILTER AT 60 MINUTE DETENTION TIME (1)(4).
(May 4 to August 2, 1971)

Parameter	Ave. or Range	No. of Samples	Standard Deviation
Temperature (^{o}C)	21-27	-	-
Flow Rate ($gal/ft^2/min$)	0.82	-	-
Recycle Ratio (2)	2.75	-	-
pH-influent	7.4	4	±0.05
effluent	7.1	4	±0.05
difference	0.3	4	±0.00
Alkalinity(mg/l as $CaCO_3$)-inf.	342	7	±8.5
eff.	237	7	±8.0
diff.	105	7	±13.5
lbs O_2/lb NH_3-N oxidized	340-510	-	-
Dissolved Oxygen(mg/l)-inf.(3)	32.5	4	±1.3
eff.	8.5	7	±2.5
total diff.(3)	84.8	7	±3.0
Organic Nitrogen(mg/l)-inf.	3.6	6	±1.3
eff.	1.5	8	±0.7
NH_3-N(mg/l)-inf.	14.3	8	±2.6
eff.	1.0	8	±0.4
percent removed	93	8	±3.1
NO_2^--N(mg/l)-eff.	0.6	8	±0.4
NO_3^--N(mg/l)-eff.	15.9	8	±3.0
Total Nitrogen(mg/l)-inf.	19.1	8	±3.0
eff.	19.5	8	±2.8
BOD(mg/l)-inf.	35(35)	5(4)	±10(5.7)
eff.	5.0	5	±3.0
percent removed	84.8	5	±9.7
COD(mg/l)-inf.	104	4	±15
eff.	51	4	±12
percent removed	51.7	4	±6.0
sol inf.- sol eff.(5)	-	-	-
Suspended Solids(mg/l)-inf.	26.5(28)	4(3)	±2.5
eff.	3.5	4	±3.6
percent removed	90.2	4	±6.5

(1) Based on untreated waste flow rate and filter void volume.
(2) Recycle Ratio = recycle flowrate/waste flowrate.
(3) Dissolved oxygen of diluted influent waste(filter entrance); Total Oxygen Used = (recycle ratio + 1)(Inf. DO - Eff. DO).
(4) Data shown in parenthesis refers to samples collected and tested by Union Sanitary District.
(5) Soluble (sol).

TABLE B-2

SUMMARY OF RESULTS FOR PREOXYGENATION FILTER
AT 40 MINUTE DETENTION TIME (1)(4).
(October 13 to November 10, 1971)

Parameter	Ave. or Range	No. of Samples	Standard Deviation
Temperature (^{o}C)	16-27	-	-
Flow Rate(gal/ft^2/min)	1.16	-	-
Recycle Ratio (2)	3.0	-	-
pH-influent	7.4	2	-
effluent	7.1	2	-
difference	0.3	2	-
Alkalinity(mg/l as $CaCO_3$)-inf.	349	11	±20
eff.	255	11	±20
diff.	95	11	±21
lbs O_2/lb NH_3-N oxidized	250-500	-	-
Dissolved Oxygen(mg/l)-inf.(3)	31.4	5	±4.5
eff.	16.9	5	±5.5
total diff.(3)	54.6	5	±2.7
Organic Nitrogen(mg/l)-inf.	-	-	-
eff.	-	-	-
NH_3-N(mg/l)-inf.	19.6	10	±4.2
eff.	5.6	10	±2.6
percent removed	70	10	±10.8
NO_2^--N(mg/l)-eff.	4.1	6	±1.3
NO_3^--N(mg/l)-eff.	6.9	6	±1.9
Total Nitrogen(mg/l)-inf.	-	-	-
eff.	-	-	-
BOD(mg/l)-inf.	46(38)	4(2)	±2.8
eff.	3.4	4	±2.2
percent removed	91.7(90)	4(2)	±4.9
COD(mg/l)-inf.	132	2	-
eff.	61	2	-
percent removed	46	2	-
sol inf.-sol eff.(5)	20.1	2	-
Suspended Solids(mg/l)-inf.	54(38)	3(3)	-
eff.	6.6	3	-
percent removed	87.3(83)	3(3)	-

(1) Based on untreated waste flow rate and filter void volume.
(2) Recycle Ratio = recycle flow rate/waste flow rate.
(3) Dissolved oxygen of diluted influent waste(filter entrance); Total Oxygen Used = (recycle ratio + 1)(Inf. DO - Eff. DO).
(4) Data shown in parenthesis refers to samples collected and tested by Union Sanitary District (influent pilot plant sampler tended to collect too many solids).
(5) Soluble (sol).

TABLE B-3

SUMMARY OF RESULTS FOR PREOXYGENATION FILTER
AT 30 MINUTE DETENTION TIME (1)(4).
(August 16 to September 28, 1971)

Parameter	Ave. or Range	No. of Samples	Standard Deviation
Temperature (^{o}C)	19-31	-	-
Flow Rate($gal/ft^2/min$)	1.29	-	-
Recycle Ratio (2)	2.0 & 3.0	-	-
pH-influent	7.3	3	-
effluent	7.0	3	-
difference	0.3	3	-
Alkalinity(mg/l as $CaCO_3$)-inf.	320	18	±61
eff.	265	18	±60
diff.	55	18	±24
lbs O_2/lb NH_3-N oxidized	240-500	-	-
Dissolved Oxygen(mg/l)-inf.(3)	24.9	11	±3.7
eff.	12.9	11	±3.3
total diff.(3)	52.4	11	±8.0
Organic Nitrogen(mg/l)-inf.	5.7	3	-
eff.	2.5	5	±0.5
NH_3-N(mg/l)-inf.	15.2	18	±3.6
eff.	6.9	18	±3.1
percent removed	55	18	±15.7
NO_2^--N(mg/l)-eff.	1.7	11	±1.3
NO_3^--N(mg/l)-eff.	6.0	11	±2.8
Total Nitrogen(mg/l)-inf.	19.6	2	-
eff.	16.4	2	-
BOD(mg/l)-inf.	53.4(37)	5(3)	±14.1
eff.	9.6	5	±5.9
percent removed	80.4(77)	5(3)	±9.2
COD(mg/l)-inf.	124	4	±10.2
eff.	54	4	±11.6
percent removed	62	4	±1.7
sol inf.-sol eff.(5)	26	4	±3.6
Suspended Solids(mg/l)-inf.	38.8(25)	7(6)	±11.0(4.5)
eff.	6.5	7	±3.0
percent removed	85.0(76)	7(6)	±5.2(3.7)

(1) Based on untreated waste flow rate and filter void volume.
(2) Recycle Ratio = Recycle flow rate/waste flow rate.
(3) Dissolved oxygen of diluted influent waste(filter etrance); Total Oxygen Use = (recycle ratio + 1)(Inf. DO - Eff. DO).
(4) Data shown in parenthesis refers to samples collected and tested by Union Sanitary District (influent pilot plant sampler tended to collect too many solids).
(5) Soluble (sol).

TABLE B-4

SUMMARY OF RESULTS FOR BUBBLE OXYGENATION FILTER AT 60 MINUTE DETENTION TIME(1)(2).
(August 11 to November 24, 1971)

Parameter	Ave. or Range	No. of Samples	Standard Deviation
Temperature (^{o}C)	16-30	-	-
Flow Rate(gal/ft^2/min)	0.22	-	-
pH-influent	7.4	1	-
effluent	7.1	1	-
difference	0.3	1	-
Alkalinity(mg/l as $CaCO_3$)-inf.	342	7	±18.2
eff.	214	7	±13.0
diff.	128	7	±25.4
lbs O_2/lb NH_3-N oxidized	260-580	-	-
O_2 Flow Rate(cfm/ft^2 at NTP)	0.08-0.12	-	-
Dissolved Oxygen(mg/l)-eff.	26.6	5	±4.1
Organic Nitrogen(mg/l)-inf.	-	-	-
eff.	-	-	-
NH_3-N(mg/l)-inf.	18.3	8	±4.2
eff.	1.76	8	±1.0
percent removed	91	8	±4.2
NO_2^--N(mg/l)-eff.	0.4	7	±0.1
NO_3^--N(mg/l)-eff.	18.4	7	±3.8
Total Nitrogen (mg/l)-inf.	-	-	-
eff.	-	-	-
BOD(mg/l)-inf.	50.5(37)	6(5)	±14.2(3.1)
eff.	9.5	8	±3.4
percent removed	79.3(75)	6(5)	±8.2(6.9)
COD(mg/l)-inf.	127	6	±18
eff.	63	9	±18.4
percent removed	56	5	±8.5
sol inf.-sol eff.(3)	29.1	7	±3.4
Suspended Solids(mg/l)-inf.	43.9(30)	6(6)	±13.6(9.6)
eff.	15.7	8	±14.0
percent removed	63.8(56)	6(6)	±43(39)

(1) Based on untreated waste flow rate and filter void volume.
(2) Data shown in parenthesis refers to samples collected and tested by Union Sanitary District (influent pilot plant sampler tended to collect too many solids).
(3) Soluble (sol).

TABLE C-1

NITROGEN DATA FOR PREOXYGENATION FILTER AT 60 MINUTE DETENTION TIME (1)

(Flow Rate - 0.82 gal/ft^2/min; Recycle Ratio - 2.75(2))

Days After Start-up	Type of Sample	Organic-N(mg/l)				NH_3-N			NO_2-N(mg/l)		NO_3-N(mg/l)		Total-N(mg/l)		pH	
		Inf.		Eff.		Inf.	Eff.	Percent								
		Total	Sol.	Total	Sol.	mg/l	mg/l	Removed	Inf.	Eff.	Inf.	Eff.	Inf.	Eff.	Inf.	Eff.
						(May 4 to August 2, 1971)										
30	grab	-	-	-	-	12.6	11.8	6	-	-	-	-	-	-	7.7	7.3
37	24 hr composite	-	-	-	-	14.0	2.1	85	-	>2.8	-	-	-	-	-	-
	grab	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
40	24 hr composite	-	-	-	-	14.9	1.7	89	0.04	2.3	-	-	-	-	-	-
	grab	-	-	-	-	12.1	2.3	81	0.02	1.5	-	-	-	-	-	-
45	24 hr composite	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	8 a.m. grab	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
48	24 hr composite	4.2	-	1.6	-	17.7	3.8	78	0.01	1.35	0.15	13.3	22.0	20.0	7.3	7.0
	11 a.m. grab	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
50	24 hr composite	4.0	-	1.2	-	14.0	1.4	90	0.18	0.75	0.1	16.7	18.3	20.1	7.3	7.1
	8 a.m. grab	-	-	-	-	13.0	1.8	86	0.00	0.55	0.1	16.0	-	-	-	-
57	24 hr composite	3.3	-	0.7	-	16.3	1.3	92	0.1	1.4	0.07	12.3	19.8	15.7	-	-
	8 a.m. grab	1.8	-	1.0	-	11.7	1.7	86	0.02	0.55	0.15	13.3	13.7	16.5	-	-
64	24 hr composite	4.0	-	1.5	-	18.3	0.6	97	0.12	0.75	0.00	22.0	22.3	24.9	-	-
	8 a.m. grab	3.9	-	1.4	-	15.3	1.4	91	0.02	0.60	0.00	17.4	19.2	20.8	7.4	7.1
70	24 hr composite	5.7	-	0.7	-	15.9	1.0	94	0.04	0.15	0.00	17.0	21.6	18.8	-	-
	6 a.m. grab	3.1	-	2.2	-	13.9	0.8	94	0.01	0.45	0.15	16.0	16.3	19.4	7.4	7.1
79	24 hr composite	-	-	2.2	-	13.2	0.8	94	-	0.4	-	14.6	-	18.0	7.5	7.2
90	10 a.m. grab	-	-	2.4	-	10.7	0.52	95	-	0.36	-	14.4	-	17.7	-	-
						(January 3 to February 10, 1972)										
249	2 p.m. grab	-	-	-	-	31.2	12.6	60	-	-	-	-	-	-	-	-
	1 to 2 days of anaerobic conditions before day 246.															
254	24 hr composite	-	-	-	-	19.3	9.4	51	-	-	-	-	-	-	-	-
	12.00 noon grab	-	-	-	-	21.7	7.4	61	-	-	-	-	-	-	-	-
261	24 hr composite	-	-	-	-	19.0	5.0	74	-	-	-	-	-	-	-	-
	11 a.m. grab	-	-	-	-	18.6	3.2	83	-	-	-	-	-	-	-	-
269	24 hr composite	-	-	-	-	17.7	4.4	75	-	-	-	-	-	-	-	-
	11 a.m. grab	-	-	-	-	14.3	3.8	73	-	-	-	-	-	-	-	-
	During day 264-268 the filter was aerobic with no influent feed.															
276	24 hr composite	-	-	-	-	19.3	6.4	67	-	-	-	-	-	-	-	-
	11 a.m. grab	-	-	-	-	18.3	5.4	70	-	-	-	-	-	-	-	-
283	24 hr composite	-	-	-	-	17.8	3.4	81	-	-	-	-	-	-	-	-
	11 a.m. grab	-	-	-	-	17.7	3.4	81	-	-	-	-	-	-	-	-

(1) Based on untreated waste flow rate and filter void volume.
(2) Recycle Ratio = recycle flow rate/waste flow rate.

TABLE C-2

MISCELLANEOUS DATA FOR PREOXYGENATION FILTER AT 60 MINUTE DETENTION TIME (1)(4)

(Flow Rate - 0.82 gal/ft^2/min; Recycle Ratio - 2.75 (2))

Days After Start-up	Temp. (°C)	Alkalinity (mg/l as $CaCO_3$) Inf.	Alkalinity (mg/l as $CaCO_3$) Eff.	lbs O_2/lb NH_3-N Oxidized	DO(mg/l) Inf.(3)	DO(mg/l) Eff.	BOD_5(mg/l) Inf. Total	BOD_5(mg/l) Inf. Sol.	BOD_5(mg/l) Eff. Total	BOD_5(mg/l) Eff. Sol.	COD(mg/l) Inf. Total	COD(mg/l) Inf. Sol.	COD(mg/l) Eff. Total	COD(mg/l) Eff. Sol.	S. S.(mg/l) Inf.	S. S.(mg/l) Eff.
		-					(May 4 to August 2, 1971)									
30	22	-	-	-	36.8	12.2	-	-	-	-	-	-	-	-	-	-
37	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	-	-	-	-	31.6	8.4	-	-	-	-	-	-	-	-	-	-
40	-	368	260	-	-	-	-	-	-	-	-	-	-	-	-	-
	22	362	268	-	36.4	12.2	-	-	-	-	-	-	-	-	-	-
45	-	-	-	-	-	-	23.4(36)	-	2.9	-	-	-	-	-	-	-
	23	-	-	-	26.8	8.8	-	-	-	-	-	-	-	-	-	-
48	-	368	250	400	-	-	-	-	-	-	-	-	-	-	-	-
	23	-	-	-	33.6	9.8	-	-	-	-	-	-	-	-	-	-
50	-	350	250	553	-	6.4	-	-	-	-	-	-	-	-	-	-
	22	342	254	621	33.6	13.6	-	-	-	-	-	-	-	-	-	-
57	-	344	238	464	-	6.0	38.6(42)	-	9.2	-	108	-	48	-	28.5(32)	1.0
	21	328	243	696	33.6	12.0	26.4	-	7.1	-	82	-	37	-	24.5	trace
64	-	346	222	343	-	5.6	>40(35)	-	3.1	-	115	-	54	-	30.0(27)	8.6
	22	338	238	437	30.4	8.0	-	-	-	-	-	-	-	-	-	-
70	-	350	230	420	-	6.8	48(28)	-	2.7	-	111	-	63.2	42.8	25(24)	3.5
	22	338	240	512	33.8	11.0	-	-	-	-	-	-	-	-	-	-
79	24	354	245	-	32.3	9.9	-	-	-	-	-	-	-	-	-	-
90	-	-	-	-	35.8	13.2	-	-	-	-	-	-	-	-	-	-
							(January 3 to February 10, 1972)									
249	17	312	216	-	35.6	18.0	-	-	-	-	-	-	-	-	-	-
	1 to 2 days of anaerobic conditions before day 246.															
254	-	320	252	-	-	-	-	-	-	-	-	-	-	-	-	-
	17	314	238	-	39.4	19.2	-	-	-	-	-	-	-	-	-	-
261	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	19	-	-	-	28.4	9.6	-	-	-	-	-	-	-	-	-	-
269	-	390	284	-	-	-	-	-	-	-	-	-	-	-	-	-
	16	326	302	-	34.4	21.2	-	-	-	-	-	-	-	-	-	-
	During day 264 to 268 the filter was aerobic with no influent feed.															
276	-	364	268	-	-	-	-	-	-	-	-	-	-	-	-	-
	18	344	268	-	29.2	13.4	-	-	-	-	-	-	-	-	-	-
283	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	19	-	-	-	28.8	12.4	-	-	-	-	-	-	-	-	-	-

(1) Based on untreated waste flow rate and filter void volume.
(2) Recycle Ratio = recycle flow rate/ waste flow rate.
(3) Dissolved oxygen of diluted influent waste (filter entrance); Total oxygen used = (recycle ratio + 1)(Inf. DO - Eff. DO).
(4) Data shown in parenthesis refers to samples collected and tested by Union Sanitary District (influent pilot plant sampler tended to collect too many solids).

TABLE C-3

NITROGEN DATA FOR PREOXYGENATION FILTER AT 40 MINUTE DETENTION TIME (1)

(Flow Rate - 1.16 gal/ft^2/min: Recycle Ratio - 3.0(2))

Days After Start-up	Type of Sample	Organic-N(mg/l)				NH_3-N			NO_2-N(mg/l)		NO_3-N(mg/l)		Total-N(mg/l)		pH	
		Inf.		Eff.		Inf.	Eff.	Percent	Inf.	Eff.	Inf.	Eff.	Inf.	Eff.	Inf.	Eff.
		Total	Sol.	Total	Sol.	mg/l	mg/l	Removed								
						(October 13 to November 10, 1971)										
164	24 hr composite	-	-	-	-	15.3	5.0	67	-	-	-	-	-	-	-	-
	3 p.m. grab	-	-	-	-	25.0	7.6	70	-	-	-	-	-	-	-	-
166	10:30 a.m. grab	-	-	-	-	-	2.8	-	-	-	-	-	-	-	-	-
	12:00 noon grab	-	-	-	-	-	3.4	-	-	-	-	-	-	-	-	-
	1:15 p.m. grab	-	-	-	-	-	5.0	-	-	-	-	-	-	-	-	-
	3:15 p.m. grab	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
173	24 hr composite	-	-	-	-	22.3	3.0	86	-	-	-	-	-	-	-	-
	11:00 a.m. grab	-	-	-	-	-	2.4	-	-	-	-	-	-	-	-	-
	5 days after backwashing at 20 to 40 gal/ft^2/min.															
179	24 hr composite	-	-	-	-	17.6	2.8	84	0.08	5.0	-	9.7	-	-	-	-
	11:00 a.m. grab	-	-	-	-	12.5	2.4	81	0.02	2.0	-	8.4	-	-	-	-
	10 days after backwashing at 20 to 40 gal/ft^2/min.															
183	24 hr composite	-	-	-	-	18.0	7.6	58	0.02	3.6	-	7.6	-	-	-	-
	1:00 p.m. grab	-	-	-	-	23.0	7.8	66	0.04	2.9	-	6.1	-	-	7.5	7.1
	15 days after backwashing at 20 to 40 gal/ft^2/min.															
186	3:00 p.m. grab	-	-	-	-	23.0	5.6	76	-	-	-	-	-	-	-	-
	2 hours after backwashing at 20 to 40 gal/ft^2/min and draining.															
191	24 hr composite	-	-	-	-	23.3	10.6	52	-	5.4	-	5.3	-	-	-	-
	11:00 a.m. grab	-	-	-	-	16.0	6.2	61	-	5.6	-	5.1	-	-	7.4	7.1

(1) Based on untreated waste flow rate and filter void volume.
(2) Recycle Ratio = recycle flow rate/waste flow rate.

TABLE C-4

MISCELLANEOUS DATA FOR PREOXYGENATION FILTER AT 40 MINUTES DETENTION TIME (1)(3)

(Flow Rate - 1.06 gal/ft^2/min; Recycle Ratio - 3.0(2))

Days After Start-up	Temp. (°C)	Alkalinity (mg/l as $CaCO_3$) Inf.	Alkalinity (mg/l as $CaCO_3$) Eff.	lbs O_2/lb NH_3-N Oxidized	DO(mg/l) Inf.(4)	DO(mg/l) Eff.	BOD_5(mg/l) Inf. Total	BOD_5(mg/l) Inf. Sol.	BOD_5(mg/l) Eff. Total	BOD_5(mg/l) Eff. Sol.	COD(mg/l) Inf. Total	COD(mg/l) Inf. Sol.	COD(mg/l) Eff. Total	COD(mg/l) Eff. Sol.	S. S. (mg/l) Inf.	S. S. (mg/l) Eff.
(October 13 to November 10, 1971)																
164	-	340	236	-	-	-	-	-	-	-	-	-	-	-	-	-
	27	384	263	-	27.4	13.2	-	-	-	-	-	-	-	-	-	-
166	-	-	-	-	35.6	22.0	-	-	-	-	-	-	-	-	-	-
	-	-	-	-	35.6	24.4	-	-	-	-	-	-	-	-	-	-
	-	-	-	-	34.8	22.8	-	-	-	-	-	-	-	-	-	-
	-	-	-	-	34.8	21.6	-	-	-	-	-	-	-	-	-	-
173	-	364	234	-	-	-	-	-	-	-	-	-	-	-	-	-
	21	348	254	251	34.2	20.8	-	-	-	-	-	-	-	-	-	-
179	-	339	222	345	-	-	47.3(36)	-	1	-	75.3	51.7	-	-	40.6(34)	7.2
	16	319	242	505	-	23.2	-	-	6.2	-	-	-	-	-	-	-
183	-	360	279	500	-	-	44(39)	-	5.0	-	151	86	68.4	61.5	56.0(36)	6.4
	23	364	272	342	25.4	11.2	-	-	-	-	-	-	-	-	-	-
186	-	362	270	-	-	-	-	-	-	-	-	-	-	-	-	-
191	-	350	280	384	-	-	43.5(50)	-	3.1	-	-	58.8	54.9	43.1	65.3(45)	6.2
	22	318	250	500	28.8	14.8	48.9	-	-	-	-	-	-	-	-	-

(1) Based on untreated waste flow rate and filter void volume.
(2) Recycle Ratio = recycle flow rate/waste flow rate.
(3) Data shown in parenthesis refers to samples collected and tested by Union Sanitary District (influent pilot plant sampler tended to collect too many solids).
(4) Dissolved oxygen of diluted influent waste (filter entrance); Total Oxygen Used = (recycle ratio + 1)(Inf. DO - EFF. DO).

TABLE C-5

NITROGEN DATA FOR PREOXYGENATION FILTER AT 30 MINUTE DETENTION TIME(1)

(Flow Rate - 1.29 gal/ft^2/min; Recycle - 2.0(2))

Days After Start-up	Type of Sample	Organic-N(mg/l)				NH_3-N			NO_2-N(mg/l)		NO_3-N(mg/l)		Total-N(mg/l)		pH	
		Inf.		Eff.		Inf.	Eff.	Percent								
		Total	Sol.	Total	Sol.	mg/l	mg/l	Removed	Inf.	Eff.	Inf.	Eff.	Inf.	Eff.	Inf.	Eff.
						(August 16 to September 28, 1971)										
96	10:00 a.m. grab	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
98	11:00 a.m. grab	-	-	-	-	11.7	7.0	40	0.01	1.0	-	-	-	-	7.2	6.9
100	48 hr composite	-	-	-	-	14.3	8.8	39	-	-	-	-	-	-	-	-
	10:00 a.m. grab	-	-	-	-	12.0	7.0	42	-	-	-	-	-	-	-	-
105	21 hr composite	5.6	-	2.1	-	15.0	8.6	43	0.00	0.55	0.1	6.4	20.7	17.7	-	-
	9:00 a.m. grab	5.3	-	2.5	-	13.0	6.0	54	0.01	0.35	0.1	6.2	18.4	15.1	-	-
111	24 hr composite	6.2	2.7	2.2	2.1	15.9	3.4	78	0.00	2.75	0.05	7.9	22.2	16.3	-	-
	10:00 a.m. grab	-	-	-	-	11.6	3.8	67	0.04	1.65	0.12	8.4	-	-	7.3	6.9
120	24 hr composite	-	-	-	-	16.7	3.4	80	0.00	1.8	-	6.4	-	-	-	-
	24 hr composite	-	-	-	-	16.3	-	-	-	-	-	-	-	-	-	-
	10:00 a.m. grab	-	-	-	-	10.0	3.2	68	0.02	0.75	-	10.2	-	-	-	-
125	24 hr composite	-	-	-	-	14.0	4.6	67	0.05	2.40	-	6.1	-	-	-	-
	24 hr composite+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	12:00 noon grab	-	-	-	-	9.6	2.4	75	0.00	0.60	-	5.1	-	-	7.3	7.1
132	24 hr composite	-	-	-	-	15.6	5.6	64	-	1.86	-	6.8	-	-	-	-
	1:00 p.m. grab	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
138	24 hr composite	-	-	-	-	18.9	11.4	40	-	-	-	-	-	-	-	-
	2:00 p.m. grab	-	-	-	-	20.8	11.3	46	-	-	-	-	-	-	-	-
		(Flow Rate - 1.72 gal/ft^2/min; Recycle Ratio - 3.0)														
		(December 2 to December 22, 1971)														
213	1:00 p.m. grab	-	-	-	-	16.3	6.4	61	-	-	-	-	-	-	-	-
218	24 hr composite	-	-	2.6	2.0	16.8	8.8	48	-	4.8	-	1.6	-	17.8	-	-
	2:00 p.m. grab	-	-	-	-	23.9	10.6	56	-	4.7	-	1.0	-	-	-	-
226	4:00 p.m. grab	-	-	3.3	2.6	19.0	-	-	-	-	-	-	-	-	-	-
233	2:00 p.m. grab	-	-	-	-	15.5	11.7	24	-	-	-	-	-	-	-	-

(1) Based on untreated waste flow rate and filter void volume.
(2) Recycle Ratio = recycle flow rate/ waste flow rate.

TABLE C-6

MISCELLANEOUS DATA FOR PREOXYGENATION FILTER AT 30 MINUTE DETENTION TIME (1)(3)

(Flow Rate - 1.29 gal/ft^2/min; Recycle Ratio - 2.0(2))

Days After Start-up	Temp. (°C)	Alkalinity (mg/l as $CaCO_3$) Inf.	Alkalinity (mg/l as $CaCO_3$) Eff.	lbs O_2/ lb NH_3-N Oxidized	DO(mg/l) Inf.(4)	DO(mg/l) Eff.	BOD_5(mg/l) Inf. Total	BOD_5(mg/l) Inf. Sol.	BOD_5(mg/l) Eff. Total	BOD_5(mg/l) Eff. Sol.	COD(mg/l) Inf. Total	COD(mg/l) Inf. Sol.	COD(mg/l) Eff. Total	COD(mg/l) Eff. Sol.	S.S.(mg/l) Inf.	S.S.(mg/l) Eff.
(August 16 to September 28, 1971)																
96	-	-	-	-	30.0	11.8	-	-	-	-	-	-	-	-	-	-
98	25	302	270	480	27.4	13.6	-	-	-	-	-	-	-	-	-	-
100	-	350	297	-	-	-	-	-	-	-	-	-	-	-	46.5(31)	5.4
	-	344	302	500	28.6	14.4	-	-	-	-	-	-	-	-	19.5	4.8
105	-	204	168	-	-	6.8	>44.7(40)	-	13	-	117	66.7	46.8	39.6	36.7(29)	7.0
	25	196	170	405	30.0	14.4	-	-	-	-	-	-	-	-	-	-
111	-	334	241	-	-	-	67(38)	-	8.5	-	138	67.5	51.9	46.0	41.1(21)	5.0
	23	320	246	380	33.4	12.8	-	-	-	-	-	-	-	-	31.3	4.2
120	-	342	246	240	-	-	56	-	5.1	-	116	69	45.2	39.2	42.7(21)	5.6
	-	-	-	-	-	-	54(32)	-	-	-	105	74	-	-	22.7(21)	-
	24	338	272	440	34.8	16.8	43	-	-	-	100	58.2	-	-	35.3	-
125	-	-	-	330	-	6.4	-	-	-	-	125	60	45.2	34.8	54.0(25)	5.6
	-	332	256	-	-	-	-	-	-	-	149	104	-	-	34.7(25)	-
	31	310	262	440	31.2	12.4	-	-	-	-	-	-	-	-	-	-
132	-	346	272	290	30.0	10.4	-	-	-	-	-	-	-	-	-	-
	27	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
138	-	472	406	455	32.4	9.4	-	-	-	-	-	-	-	-	-	-
	27	380	347	-	-	-	-	-	-	-	-	-	-	-	-	-
(Flow Rate - 1.72 gal/ft^2/min; Recycle Ratio - 3.0) (December 2 to December 22, 1971)																
213	19	329	273	-	28.0	15.6	-	-	-	-	-	-	-	-	-	-
218	-	290	236	-	-	-	34.2(36)	-	9.8	-	134	62.8	58.5	53.0	57(38)	8.0
	21	260	182	-	25.4	12.4	55.0(39)	-	-	-	142	63.8	-	-	70(52)	-
226	20	322	328	-	21.8	10.4	66.8(47)	17.3	12.1	5.7	133	83.8	75.1	59.3	73(44)	13.3
233	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

(1) Based on untreated waste flow rate and filter volume.
(2) Recycle Ratio = recycle flow rate/waste flow rate.
(3) Data shown in parenthesis refers to samples collected and tested by Unico Sanitary District (influent pilot plant sampler tended to collect too many solids,.
(4) Dissolved oxygen of diluted influent waste (filter entrance); Total Oxygen Used = (recycle ratio + 1) (Inf. DO - Eff. DO).

TABLE C-7

NITROGEN DATA FOR BUBBLE OXYGENATION FILTER AT 60 MINUTE DETENTION TIME (1)

(Flow Rate - 0.22 gal/ft^2/min)

Days After Start-up	Type of Samples	Organic-N(mg/l)				NH_3-N			NO_2-N(mg/l)		NO_3-N(mg/l)		Total-N(mg/l)		pH	
		Inf.		Eff.		Inf.	Eff.	Percent	Inf.	Eff.	Inf.	Eff.	Inf.	Eff.	Inf.	Eff.
		Total	Sol.	Total	Sol.	mg/l	mg/l	Removed								
						(August 11 to November 24, 1971)										
6	Seed: grab	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
20	10:00 a.m. grab	-	-	-	-	12.0	13.0	-	-	-	-	-	-	-	-	-
25	9:00 a.m. grab	5.3	-	2.2	-	13.0	11.3	13	0.01	0.60	0.1	1.6	18.4	15.7	-	-
32	10:00 a.m. grab	-	-	2.5	-	11.6	9.9	15	0.04	1.95	0.12	2.8	-	17.2	7.3	6.8
41	10:00 a.m. grab	-	-	-	-	10.0	3.0	70	0.02	2.45	-	8.6	-	-	-	-
46	2:00 p.m. grab	-	-	-	-	9.6	0.4	96	0.00	0.3	-	9.2	-	-	7.3	7.0
53	1:00 p.m. grab	-	-	-	-	-	3.0	-	-	0.6	-	16.0	-	-	-	-
59	2:00 p.m. grab	-	-	-	-	20.8	6.1	71	-	-	-	-	-	-	-	-
74	24 hr composite	-	-	-	-	15.3	8.5	44	-	-	-	-	-	-	-	-
	3:00 p.m. grab	-	-	-	-	25.0	7.7	69	-	-	-	-	-	-	-	-
76	10:30 a.m. grab	-	-	-	-	-	1.2	-	-	-	-	-	-	-	-	-
	12:00 noon	-	-	-	-	-	2.2	-	-	-	-	-	-	-	-	-
	1:15 p.m.	-	-	-	-	-	3.0	-	-	-	-	-	-	-	-	-
	3:15 p.m.	-	-	-	-	-	4.4	-	-	-	-	-	-	-	-	-
83	24 hr composite	-	-	-	-	22.3	1.4	94	-	-	-	-	-	-	-	-
	11:00 a.m. grab	-	-	-	-	-	0.6	-	-	-	-	-	-	-	-	-
89	24 hr composite	-	-	-	-	17.6	1.9	89	-	0.6	-	17.6	-	-	-	-
	11:00 a.m. grab	-	-	-	-	12.5	0.5	96	-	0.3	-	12.9	-	-	-	-
94	24 hr composite	-	-	-	-	18.0	1.0	94	0.02	0.45	-	19.8	-	-	-	-
	1:00 p.m. grab	-	-	-	-	23.0	3.8	83	0.04	0.55	-	24.1	-	-	-	-
102	24 hr composite	-	-	4.6	2.1	23.3	2.6	89	-	0.3	-	22.0	-	29.5	-	-
	11:00 a.m. grab	-	-	-	-	16.0	1.9	88	-	0.15	-	15.4	-	-	7.4	7.1
116	24 hr composite	8.8	-	-	-	13.7	1.0	93	0.18	0.4	0.23	17.4	22.9	-	7.6	7.1

(1) Based on untreated waste flow rate and filter void volume.

TABLE C-8

MISCELLANEOUS DATA FOR BUBBLE OXYGENATION FILTER AT 60 MINUTE DETENTION TIME (1)(2)

(Flow Rate - 0.22 gal/ft^2/min)

Days After Start-up	Temp. (°C)	Alkalinity (mg/l as $CaCO_3$) Inf.	Alkalinity (mg/l as $CaCO_3$) Eff.	O_2 Feed (cfm/ft^2) at NTP	lbs O_2/lb NH_3-N Oxidized	DO Eff. mg/l	BOD_5(mg/l) Inf. Total	BOD_5(mg/l) Inf. Sol.	BOD_5(mg/l) Eff. Total	BOD_5(mg/l) Eff. Sol.	COD(mg/l) Inf. Total	COD(mg/l) Inf. Sol.	COD(mg/l) Eff. Total	COD(mg/l) Eff. Sol.	S:S.(mg/l) Inf.	S:S.(mg/l) Eff.
					(August 11 to November 24, 1971)											
6	-	-	-	-	-	21.6	-	-	-	-	-	-	-	-	-	-
20	-	344	342	0.014	-	16.0	-	-	-	-	-	-	-	-	-	-
25	23	204	172	0.014	490	14.8	44(40)	-	13	-	117	67	48.6	39.6	37(29)	9.5
32	22	320	295	0.014	490	8.2	67(38)	-	10.7	-	138	68	54.5	50.2	31.3(21)	3.6
41	23	338	274	0.020	200	11.6	56(32)	-	7.1	-	100	58	42.6	34.0	35.3(21)	5.6
46	30	310	249	0.027	200	16.0	-	-	-	-	125	60	74.8	30.5	35(25)	34.7
53	24	-	-	0.028	-	20.4	-	-	-	-	-	-	-	-	-	-
59	24	380	274	0.028	129	9.6	-	-	-	-	-	-	-	-	-	-
74	-	340	260	-	-	-	-	-	-	-	-	-	-	-	-	-
	24	384	249	-	-	9.2	-	-	-	-	-	-	-	-	-	-
76	-	-	-	-	-	16.8	-	-	-	-	-	-	-	-	-	-
	-	-	-	-	-	20.	-	-	-	-	-	-	-	-	-	-
	-	-	-	-	-	19.2	-	-	-	-	-	-	-	-	-	-
	-	-	-	-	-	17.6	-	-	-	-	-	-	-	-	-	-
83	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	19	-	-	0.081	263	29.6	-	-	-	-	-	-	-	-	-	-
89	-	339	219	-	-	-	47.3(36)	-	4.7	-	132	77.3	-	48.6	40.6(34)	-
	16	319	222	0.091	503	24.4	-	-	6.2	-	-	-	53.6	-	-	3.4
94	-	360	220	-	-	-	44(39)	-	7.8	-	151	86	58.6	50.8	56.0(36)	10.0
	21	364	190	0.084	294	21.2	-	-	12.4	-	-	-	80.0	54.7	-	20
102	-	350	208	-	-	-	43.5	-	-	-	-	58.8	51.0	27.4	65.3(45)	38.7
	20	318	210	0.124	587	31.6	48.9	-	14.0	3.5	-	-	99.9	25.4	-	-
116	-	343	230	-	-	26.2	-	-	-	-	-	-	-	-	-	-

(1) Based on untreated waste flow rate and filter void volume.
(2) Data shown in parenthesis refers to samples collected and tested by Union Sanitary District (influent pilot plant sampler tended to collect too many solids).

TABLE C-9

NITROGEN DATA FOR BUBBLE OXYGENATION FILTER AT 30 MINUTE DETENTION TIME

(November 26, 1971 - February 10, 1972)

Days After Start-up	Type of Sample	Temp. (°C)	Flow Rate (gpm/ft^2)	Detention Time (min)(1)	Organic-N(mg/l)				NH_3-N		
					Inf.		Eff.		Inf.	Eff.	Percent
					Total	Sol.	Total	Sol.	mg/l	mg/l	Removal
118	1:00 p.m. grab	-	0.44	30	-	-	-	-	-	8.0	-
	Filter oxygen failure between day 118 and 122 (length of time unknown).										
124	2:00 p.m. grab	18	0.44	30	-	-	-	-	16.3	14.1	13.5
129	24 hr composite	-	0.44	30	-	-	-	-	16.8	13.6	19
	2:00 p.m. grab	19	0.44	30	-	-	5.81	2.12	23.9	18.3	15
137	4:00 p.m. grab	-	0.44	30	-	-	6.67	2.52	19.0	25.5	-
144	2:00 p.m. grab	-	0.44	30	-	-	-	-	15.5	9.0	42
	Before day 157 the filter was anaerobic (solids very black) for 1 to 7 days.										
160	2:00 p.m. grab	17	0.44	30	-	-	-	-	31.2	25.9	20.2
165	24 hr composite	-	0.44	30	-	-	-	-	19.3	18.3	5
	12:00 noon grab	17	0.44	30	-	-	-	-	21.7	17.6	19
172	24 hr composite	-	0.44	30	-	-	-	-	18.6	8.6	59.0
	11:00 a.m. grab	18	0.44	30	-	-	-	-	19.0	14.0	26.0
180	24 hr composite	-	0.44	30	-	-	-	-	17.7	11.3	36
	11:00 a.m. grab	15	0.44	30	-	-	-	-	14.3	7.7	46
	After 4 days of idle aerobic conditions (day 175 to 179).										
187	24 hr composite	-	0.44	30	-	-	-	-	19.3	14.2	26
	11:00 a.m. grab	18	0.44	30	-	-	-	-	18.3	9.6	47
	During day 185 and 186 the filter was without any influent waste or oxygen feed.										
194	24 hr composite	-	0.22	60	-	-	-	-	17.8	3.0	83
	11:00 a.m. grab	17	0.22	60	-	-	-	-	17.7	2.3	87

(1) Based on untreated waste flow rate and filter void volume.

TABLE C-10

MISCELLANEOUS DATA FOR BUBBLE OXYGENATION FILTER AT 30 MINUTE DETENTION TIME(1)

(November 26, 1971 - February 10, 1972)

Days After Start-up	Alkalinity mg/l as $CaCO_3$		DO Eff. mg/l	BOD_5 (mg/l)				COD (mg/l)				S.S.	
				Inf.		Eff.		Inf.		Eff.			
	Inf.	Eff.		Total	Sol.	Total	Sol.	Total	Sol.	Total	Sol.	Inf. mg/l	Eff. mg/l
118	-	-	-	-	-	-	-	-	-	-	-	-	-
	Filter oxygen failure between day 118 and 122 (length of time unknown).												
124	329	313	28.8	-	-	-	-	-	-	-	-	-	-
129	290	267	-	34(36)	-	-	-	134	63	-	45	57(38)	-
	260	212	23.4	55(39)	-	20.4	5.3	142	64	100	-	70(52)	53
137	322	372	17.4	67(47)	17.3	26.5	5.9	133	84	59	-	73(44)	49
144	-	-	-	-	-	-	-	-	-	-	-	-	-
	Before day 157 filter was anaerobic (solids very black) for 1 to 7 days.												
160	312	298	-	-	-	-	-	-	-	-	-	-	-
165	320	310	-	-	-	-	-	-	-	-	-	-	-
	314	284	31.0	-	-	-	-	-	-	-	-	-	-
172	-	-	-	-	-	-	-	-	-	-	-	-	-
	-	-	22.8	-	-	-	-	-	-	-	-	-	-
180	390	330	-	-	-	-	-	-	-	-	-	-	-
	326	293	28.8	-	-	-	-	-	-	-	-	-	-
	After 4 days of idle aerobic conditions (day 175 to 179).												
187	364	318	-	-	-	-	-	-	-	-	-	-	-
	344	290	21.2	-	-	-	-	-	-	-	-	-	-
	During day 185 and 186 the filter was without any influent waste or oxygen feed.												
194	-	-	-	-	-	-	-	-	-	-	-	-	-
	341	204	28.4	-	-	-	-	-	-	-	-	-	-

(1) Data shown in parenthesis refers to samples collected and tested by Union Sanitary District (influent pilot plant sampler tended to collect too many solids).

TABLE D-1

PREOXYGENATION FILTER(4)

(Grab Samples Every 2-Hours Over a 24-Hour Period)

(Detention Time - 60 Minutes (1); Recycle Ratio 2.75 (2); After 79 Days of Operation)

Date (1972)	Hour	Temp. (°C)	pH		Alkalinity		DO		NH_3-N			NO_2-N	NO_3-N
			Inf.	Eff.	Inf. mg/l	Eff. mg/l	Inf.(3) mg/l	Eff. mg/l	Inf. mg/l	Eff. mg/l	Percent Removed	Eff. mg/l	Eff. mg/l
7/22	8 p.m.	27	7.45	7.13	358	234	31.6	5.6	13.6	1.3	90	0.50	15.0
7/22	10 p.m.	25	7.45	7.10	352	238	32.0	8.4	13.0	0.90	93	0.38	14.5
7/22	Midnight	23	7.50	7.30	358	240	32.6	10.2	12.3	0.90	93	0.36	14.1
7/23	2 a.m.	23	7.65	7.20	345	240	32.8	10.8	12.0	0.80	93	0.36	15.3
7/23	4 a.m.	23	7.45	7.20	344	241	33.2	11.2	12.0	0.40	96	0.36	15.1
7/23	6 a.m.	23	7.50	7.20	351	244	32.2	11.8	11.4	0.80	93	0.32	14.3
7/23	8 a.m.	23	7.50	7.15	344	245	33.2	13.0	10.3	1.0	90	0.32	13.3
7/23	10 a.m.	23	7.45	7.15	350	259	32.8	13.6	9.3	0.40	96	0.28	12.8
7/23	Noon	23	7.40	7.15	338	260	32.4	13.6	10.7	0.50	94	0.26	12.6
7/23	2 p.m.	24	7.50	7.20	364	252	32.4	9.2	17.0	1.0	94	0.44	14.6
7/23	4 p.m.	26	7.50	7.15	374	240	31.8	6.0	19.0	1.2	94	0.62	16.1
7/23	6 p.m.	26	7.50	7.05	372	243	30.8	5.6	18.0	1.2	93	0.58	17.3
Average:		24	7.49	7.17	354	245	32.3	9.9	13.2	0.87	93	0.4	15.0
Composite Sample:						245		5.6		0.1		0.08	14.1

(1) Based on untreated waste flow rate and filter void volume.
(2) Recycle Ratio = recycle flow rate/waste flow rate.
(3) Dissolved oxygen of diluted influent waste (filter entrance);
Total Oxygen Used = (recycle ratio + 1)(Inf. DO - Eff. DO).
(4) Unless otherwise defined inf. = undiluted and untreated waste.

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TABLE D-2

BUBBLE OXYGENATION FILTER

(Grab Samples Every 2-Hours Over a 24-Hour Period)

(Detention Time - 60 Minutes(1); After 116 Days of Operation)

Date (1972)	Hour	Temp. (°C)	pH		Alkalinity		DO	NH_3-N			NO_2-N	NO_3-N	Remarks
			Inf.	Eff.	Inf. mg/l	Eff. mg/l	Eff. mg/l	Inf. mg/l	Eff. mg/l	Percent Removed	Eff. mg/l	Eff. mg/l	
11/23	4:00 p.m.	20	-	-	376	248	18.4	18.7	6.1	67	0.60	18.4	1-1/2 hrs. after back-wash.
11/23	6:00 p.m.	19	7.65	6.90	362	212	20.6	15.8	1.88	88	0.60	19.4	
11/23	8:00 p.m.	19	7.65	6.90	356	224	24.4	13.0	1.06	92	0.45	17.8	
11/23	10:00 p.m.	18	7.55	7.00	346	232	24.8	13.0	0.75	94	0.45	16.9	
11/23	Midnight	18	7.58	7.00	346	234	26.6	13.0	0.81	94	0.42	17.0	
11/24	2:00 a.m.	17	7.62	7.10	340	230	27.0	12.3	0.75	94	0.40	15.6	
11/24	4:00 a.m.	17	7.55	7.10	336	234	28.2	12.0	0.87	93	0.40	15.3	
11/24	6:00 a.m.	16	7.50	7.15	333	234	29.6	13.6	0.81	94	0.40	18.8	
11/24	8:00 a.m.	17	7.55	7.10	326	234	30.8	10.7	0.87	92	0.35	18.0	
11/24	10:00 a.m.	18	7.53	7.15	322	234	31.6	9.3	0.69	92	0.30	17.3	
11/24	Noon	19	7.50	7.10	334	229	28.4	14.0	1.19	91	0.37	14.5	
11/24	2:00 p.m.	19	7.60	7.08	360	211	24.2	18.7	1.56	92	0.35	19.5	
Average:		18	7.57	7.05	343	230	26.2	13.7	1.44 (1.02)(2)	89 (93)(2)	0.44	17.4	
Composite Sample:								13.7					

(1) Based on untreated waste flow rate and filter void volume.

(2) Not counting data affected by backwashing (4:00 to 6:00 p.m.).